CHAPTER 7

ENERGY DISSIPATORS

22 February 2000

Chapter 7 - Energy Dissipators

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7.1 Energy Dissipators Introduction

7.1.1 Overview

The failure or damage of many culverts and detention basin outlet structures can be traced to unchecked erosion. Erosive forces which are at work in the natural drainage network are often exacerbated by the construction of a highway or by other urban development. Interception and concentration of overland flow and constriction of natural waterways inevitably results in an increased erosion potential. To protect the culvert or other outlet device and adjacent areas, it is sometimes necessary to employ an energy dissipator.

A common failure made at storm sewer outlets to streams is erosion of the area immediately beneath the outlet of the storm sewer. Design to resist this failure mode is presented in section 7.10.

7.1.2 Definition

Energy dissipators are any device designed to protect downstream areas from erosion by reducing the velocity of flow to acceptable limits.

7.1.3 Purpose

This chapter provides:

- Design procedures which are based on FHWA Hydraulic Engineering Circular Number 14 (HEC 14) "Hydraulic Design of Energy Dissipators for Culverts and Channels," September 1983, revised in 1995.
- Results of analysis using the HYDRAIN system and the HY8 software.

7.1.4 Symbols

Table 7-1 Symbols, Definitions And Units

Symbol	Definition	Units
A	Cross sectional area	ft^2
A_o	Area of flow at culvert outlet	ft^2
d_E	Equivalent depth at brink	ft
d_o	Normal flow depth at brink	ft
D	Height of culvert	ft
d_{50}	Mean diameter of riprap	ft
DI	Discharge Intensity Modified	-
Fr	Froude Number	-
g	Acceleration due to gravity	ft/s^2
h_S	Depth of dissipator pool	ft
L	Length of culvert	ft
L_B	Overall length of basin	ft
L_S	Length of dissipator pool	ft
Q	Rate of discharge	cfs
Q_{OT}	Overtopping flow	cfs
S_o	Slope of streambed	ft/ft
TW	Tailwater depth	ft
V_d	Velocity downstream	ft/s
V_L	Velocity — (L) feet from brink	ft/s
V_o	Normal velocity at brink	ft/s
W_B	Width of basin	ft
W_o	Diameter or width of culvert	ft
W_S	Width of scour hole	ft

7.2 Design Criteria

7.2.1 Overview

Energy dissipators should be employed whenever the velocity of flow leaving a stormwater management facility exceeds the erosion velocity of the downstream channel system. Several standard energy dissipator designs have been documented by the U.S. Department of Transportation including hydraulic jump, forced hydraulic jump, impact basins, drop structures, stilling wells, and riprap. This chapter will concentrate on those energy dissipators most applicable to urban stormwater management problems. In addition, throughout this chapter culvert outlets will be referred for energy dissipation design. However, dissipators can be used downstream from any outlet device.

7.2.2 Dissipator Type Selection

The dissipator type selected for a site must be appropriate to the location. In this chapter, the terms “internal” and “external” are used to indicate the location of the dissipator in relationship to the culvert. An external dissipator is located outside of the culvert and an internal dissipator is located within the culvert barrel.

1. Internal dissipators

Containing the hydraulic jump within the culvert is a form of internal energy dissipation. The Nebraska Department of Roads has issued a report titled "Hydraulic Analysis of Broken-Back Culverts" (January 1998) that contains a design procedure for this type of culvert.

Internal dissipators are used where:

- the scour hole at the culvert outlet is unacceptable,
- the right-of way is limited,
- debris is not a problem, and
- moderate velocity reduction is needed.

2. Natural scour holes

Natural scour holes are used where:

- undermining of the culvert outlet will not occur or it is practicable to be checked by a cutoff wall,
- the expected scour hole will not cause costly property damage, and
- there is no nuisance effect.

3. External dissipators

External dissipators are used where:

- the outlet scour hole is not acceptable,
- moderate amount of debris is present, and
- the culvert outlet velocity (V_o) is moderate, $Fr < 3$.

4. Stilling Basins

Stilling Basins are used where:

- the outlet scour hole is not acceptable,
- debris is present, and
- the culvert outlet velocity (V_o) is high, $Fr > 3$.

7.2.3 Design Limitations

Ice Buildup

If ice buildup is a factor, it shall be mitigated by:

- sizing the structure to not obstruct the winter low flow, and
- using external dissipators.

Debris Control

Debris control shall be designed using Hydraulic Engineering Circular No. 9, "Debris-Control Structures" and shall be considered:

- where clean-out access is limited, and
- if the dissipator type selected cannot pass debris.

Flood Frequency

The flood frequency used in the design of the energy dissipator device shall be the same flood frequency used for the culvert design. The use of a greater frequency is permitted, if justified by:

- low risk of failure of the crossing,
- substantial cost savings,
- limited or no adverse effect on the downstream channel, and
- limited or no adverse effect on downstream development.

Maximum Culvert Exit Velocity

The culvert exit velocity shall be consistent with the maximum velocity in the natural channel or shall be mitigated by using:

- channel stabilization (See Chapter 5, Open Channels), and
- energy dissipation.

Tailwater Relationship

The hydraulic conditions downstream shall be evaluated to determine a tailwater depth and the maximum velocity for a range of discharges. Refer to:

- Open channels (See Chapter 5, Open Channels).
- Lake, pond, or large water body shall be evaluated using the high water elevation that has the same frequency as the design flood for the culvert. (See Lincoln Flood Insurance Study for the appurtenant stream information).

7.2.4 Design Options

Material Selection

The material selected for the dissipator shall be based on a comparison of the total cost over the design life of alternate materials and shall not be made using first cost as the only criteria. This comparison shall consider replacement cost and the difficulty of construction as well as traffic delay.

Culvert Outlet Type

In choosing a dissipator, the selected culvert end treatment has the following implications.

- Culvert ends which are projecting or mitered to the fill slope offer no outlet protection.
- Headwalls provide embankment stability and erosion protection. They provide protection from buoyancy and reduce damage to the culvert.
- Commercial end sections add little cost to the culvert and may require less maintenance, retard embankment erosion and incur less damage from maintenance.
- Aprons do not reduce outlet velocity, but if used shall extend at least one culvert height downstream. They shall not protrude above the normal streambed elevation.
- Wingwalls are used where the side slopes of the channel are unstable, where the culvert is skewed to the normal channel flow, to redirect outlet velocity, or to retain fill.

Safety Considerations

Traffic shall be protected from external energy dissipators by locating them outside the appropriate "clear zone" distance per the AASHTO Roadside Design Guide or shielding them with a traffic barrier.

Weep Holes

If weep holes are used to relieve uplift pressure, they shall be designed in a manner similar to underdrain systems.

7.2.5 Related Designs

Culvert

The culvert shall be designed independently of the dissipator design (see Design of Culverts, Chapter 4) with the exception of internal dissipators which may require an iterative solution. The culvert design shall be completed before the outlet protection is designed and shall include computation of outlet velocity.

Downstream Channel

The downstream channel protection shall be designed concurrently with dissipator design (See Chapter 5, Open Channel Hydraulics).

7.2.6 Computational Methods

Charts

- Charts are required for a manual solution.
- Charts required for the design of scour holes, riprap basins, USBR type VI impact basins and SAF basins are included in this Chapter. Charts required for the design of other types of energy dissipators are found in HEC 14.

Computer Software

- HY-8 (FHWA Culvert Analysis Software) Version 4.1 or greater, contains an energy dissipator module which can be used to analyze most types of energy dissipators in HEC 14.

7.3 Design Equations

7.3.1 Culvert Outlet Conditions

The culvert design establishes the outlet flow conditions. However, these parameters may require closer analysis for energy dissipator design.

Depth (ft), d_o.

- The normal depth assumption should be reviewed and a water surface profile calculated if $L < 50\ d_o$.
- The brink depth (see HEC 14 for curves) should be used for mild slopes and low tailwater, not critical depth.

Area (ft^2), A_o.

The cross sectional area of flow at the culvert outlet should be calculated using (d_o).

Velocity (ft/s), V_o

The culvert outlet velocity should be calculated as follows:

$$V_o = Q/A_o \tag{7.1}$$

Where: Q = discharge, cfs

Froude Number, Fr

The Froude number is a flow parameter traditionally used to design energy dissipators and is calculated using:

$$Fr = V_o/[(g\ d_o)^{0.5}] \tag{7.2}$$

Where: g = acceleration of gravity, 32.2 ft/s^2

Equivalent Depth (ft), $d_E = (A_o/2)^{0.5}$

Equivalent depth is an artificial depth calculated for culverts which are not rectangular so a reasonable Fr can be determined.

Discharge Intensity, DI_c.

Discharge intensity is a flow parameter similar to Fr, used for circular culverts of diameter (D) which are flowing full.

$$DI_c = Q/(g^{0.5}D^{2.5}) \tag{7.3}$$

Discharge Intensity Modified, DI.

Referring to the new Chapter V, HEC 14, 1995, the Modified Discharge Intensity, DI, for all culvert shapes are:

$$DI = Q/(g^{0.5}\ R_c^{\ 2.5}) \tag{7.4}$$

Where: Q = discharge, cfs
A_c = culvert area, ft^2
P_c = culvert perimeter, ft
$R_c = (A_c/P_c)$

7.3.2 Scour Hole Estimation

Chapter V of HEC 14 (revised version, 1995) contains an estimating procedure for scour hole geometry based on soil, flow data and culvert geometry. This scour prediction procedure is intended to serve together with the maintenance history and site reconnaissance information for determining energy dissipator needs.

Only scour holes on cohesionless material will be discussed in this Chapter. For scour holes on cohesive soil, the designer can refer to the above-mentioned Chapter V, HEC 14 for detail.

The results of the tests made by the US Army Waterways Experiment Station, Vicksburg, Mississippi indicate that the scour hole geometry varies with the tailwater conditions. The maximum scour geometry occurs at tailwater depths less than half the culvert height. The maximum depth of scour, d_S, occurs at a location approximately $0.4L_S$ downstream of the culvert, where L_S is the length of the scour.

The following empirical equations defining the relationship between the culvert discharge intensity, time and the length, width, depth and volume of the scour hole are presented for the maximum or extreme scour case.

Where: d_S = maximum depth of scour hole, ft
L_S = length of scour hole, ft
W_S = width of scour hole, ft

$$\left[\frac{d_s}{R_c}, \frac{W_s}{R_c}, \frac{L_s}{R_c}\right] = C_s C_h \left(\frac{\alpha}{\sigma^{1/3}}\right)\left(\frac{Q}{\sqrt{g}R_c^{2.5}}\right)^{\beta}\left(\frac{t}{316}\right)^{\theta} \tag{7.5}$$

$$d_S,\ W_S,\ \text{or}\ L_S = (F_1)(F_2)(F_3)R_c \tag{7.6}$$

Where:

$$F_1 = C_s C_h\left(\frac{\alpha}{\sigma^{1/3}}\right)$$

$$F_2 = \left(\frac{Q}{\sqrt{g}R_c^{2.5}}\right)^{\beta} = (DI)^{\beta}$$

$$F_3 = \left(\frac{t}{316}\right)^{\theta}$$

Where: t = 30 min or the time of concentration, if longer
R_c = hydraulic radius of drainage structure flowing full
σ = material standard deviation, generally, σ = 2.10 for gravel and 1.87 for sand
α, ß, θ, C_S and C_h are coefficients, as shown in Table 7-2
F_1 , F_2 and F_3 are factors to aid the computation, as shown in Step 7B, Figure 7-1

7.4 Design Procedure

The following design procedures are intended to provide a convenient and organized method for designing energy dissipators by hand. The designer should be familiar with all the equations in section 7.3 before using these procedures. In addition, application of the following design method without an understanding of hydraulics can result in an inadequate, unsafe, or costly structure.

Step 1: Assemble Site Data And Project File

Step 2: Determine Hydrology

Step 3: Select Design Q

Step 4: Design Downstream Channel

a. Determine channel slope, cross section, normal depth and velocity.
b. Check bed and bank materials stability.

Step 5: Design Culvert/Outlet

Step 6: Summarize Data On Design Form, Figure 7-1

Step 7: Estimate Scour Hole Size

a. Enter input for scour equation on Figure 7-1.
b. Calculate d_S, W_S, L_S , using equations 7.5 or 7.6

Step 8: Determine Need For Dissipator

An energy dissipator is needed if:

a. the estimated scour hole dimensions, which exceed the allowable right-of-way, undermine the culvert cutoff wall, or present a safety or aesthetic problem;
b. downstream property is threatened; or
c. V_o is much greater than V_d.

Step 9: Select Design Alternative

a. Calculate Froude number, Fr.
b. Choose energy dissipator types.
If Fr > 3, design a SAF stilling basin.
If Fr < 3, design a riprap basin or design a USBR Type VI, if Q < 400 cfs for each barrel and little debris is expected. If these are not acceptable or economical, try other dissipators in HEC 14.

Step 10: Design Dissipators

a. Use the following design procedures and charts:
   - Section 7.6 for the SAF.
   - Section 7.7 for the RIPRAP.
   - Section 7.8 for the USBR Type VI, (Baffled Outlet)
   - Section 7.9 for the Riprap Aprons.

Step 11: Design Riprap Transition

a. Most dissipators require some protection adjacent to the basin exit.
b. The length of protection can be judged based on the difference between V_o and V_d. The riprap should be designed using HEC 11.

Step 12: Review Results

a. If downstream channel conditions (velocity, depth and stability) are exceeded, either:
   - design riprap for channel, Step 4, or
   - select another dissipator, Step 9.

b. If preferred energy dissipator affects culvert hydraulics, return to Step 5 and calculate culvert performance.

c. If debris-control structures are required upstream, consult HEC 9.

d. If a check Q was used for the culvert design, assess the dissipator performance with this discharge.

Step 13: Documentation

Table 7-2

A. Coefficient for Culvert Outlet Scour - Cohesionless Materials

	α	β	θ
Depth, d_S	2.27	0.39	0.06
Width, W_S	6.94	0.53	0.08
Length, L_S	17.10	0.47	0.10
Volume, V_S	127.08	1.24	0.18

B. Coefficient C_S for Outlets Above the Bed

H_S	Depth	Width	Length	Volume
0	1.00	1.00	1.00	1.00
1	1.22	1.51	0.73	1.28
2	1.26	1.54	0.73	1.47
4	1.34	1.66	0.73	1.55
H_S is the height above bed in pipe diameters, ft				

C. Coefficient C_h for Culvert Slope

Slope %	Depth	Width	Length	Volume
0	1.00	1.00	1.00	1.00
2	1.03	1.28	1.17	1.30
5	1.08	1.28	1.17	1.30
>7	1.12	1.28	1.17	1.30

Figure 7-1 : ENERGY DISSIPATOR CHECKLIST

Project No. ____________________ Designer ____________
Date ________
Reviewer ____________________ Date ________

SCOUR EQUATIONS

$$\frac{d_S}{R_c}, \frac{W_S}{R_c}, \frac{L_S}{R_c} = C_S C_h \left[\frac{\alpha}{\sigma^{1/3}}\right]\left[\frac{Q}{g^{.5} R_c^{2.5}}\right]^{\beta}\left[\frac{t}{316}\right]^{\theta}$$

$$d_S, W_S, L_S = [C_S C_h \alpha/\sigma^{1/3}][DI]^{\beta}[t/316]^{\theta} R_c$$

$$d_S, W_S, L_S = [F_1]\,[F_2]\,[F_3]\,R_c$$

STEP 7A - EQUATION INPUT DATA

FACTOR	VALUE
Q = Discharge, cfs	
A_c= Culvert area, ft^2	
P_c= Perimeter, ft	
$R_c = A_c / P_c$	
DI= Discharge Intensity	
t = time of concentration	

STEP 6 - DATA SUMMARY

Parameters	Culvert	Channel
Station		
Control		
Type		
Height, D		
Width, B		
Length, L		
Material		
Manning's n		
Side Slope		
Discharge, Q		
Depth, d		
Velocity, V		
$Fr=V/(gd)^{0.5}$		
Flow Area, A		
Slope		

STEP 7B - SCOUR COMPUTATION

Factor	Depth	Width	Length
α			
β			
θ			
F_1			
F_2			
F_3			
$[F_1][F_2][F_3]R_c$			
Allowable			

If calculate scour > Allowable and:

1. Fr > 3, design a SAF basin
2. Fr < 3, design a riprap basin
3. Fr < 3, design a USBR type VI

7.5 Design Example

7.5.1 Design Example Steps

Step 1: Assemble Site Data And Project File

a. Site survey - The culvert project file contains USGS site and location maps, roadway profile and embankment cross sections. Site visit notes indicate no sediment or debris problems and no nearby structures.

b. Studies by other agencies - none.

c. Environmental, risk assessment shows no problems.

d. Design criteria:
- 25-year frequency for design, and
- 100-year frequency for check.

Step 2: Determine Hydrology

For the purpose of this example, use
- Q_{25} = 400 cfs
- Q_{100} = 500 cfs

Step 3: Select Design Q

Use Q_{25} = 400 cfs, as requested by the design criteria.

Step 4: Design Downstream Channel

a. Cross section of channel with slope = 0.05 ft/ft

Point	Station, ft	Elevation, ft
1	12	180
2	22	175
3	32	174.5
4	34	172.5
5	39	172.5
6	41	174.5
7	51	175
8	61	180

b. Rating Curve for Channel

Calculated using methods contained in Chapter 5.

Q (cfs)	TW (ft)	V (ft/s)
100	1.4	11
200	2.1	14
300	2.5	16
400	2.8	18
500	3.1	19

c. At a V_{25} = 18 ft/s, the 3-inch gravel material which makes up the channel boundary is not stable and riprap is needed (See Chapter 5, Open Channels) for a transition.

Step 5: Design Culvert

A 7 ft × 6 ft RCB with a beveled entrance on a slope of 0.05 ft/ft was the selected design. The FHWA HY8 program showed that this culvert is operating at inlet control and has:

	Q (cfs)	HW_i (ft)	V_o (ft/s)
Q_{25} =	400	7.6	32
Q_{ot} =	430	8.5	
Q_{100} =	500	8.6	34

Step 6: Summarize Data On Design Form

See Figure 7-2.

Step 7: Size Scour Hole

The size of the scour hole is determined using equations 7.5 and 7.6. For channel with gravel bed, the standard deviation of the material, σ is 2.10. Table 7-2 shows that the value of C_S =1.00 and C_h = 1.08 for depth, 1.28

for width, 1.17 for length and 1.30 for volume calculations. See Figure 7-2 for a summary of the computation.

Step 8: Determine Need For Dissipator
The scour hole dimensions are excessive, and since V_o = 32 ft/s is much greater than V_d = 18 ft/s, an energy dissipator is needed.

Step 9: Select Design Alternative
Since the Fr > 3, an SAF stilling basin should be used.

Step 10: Design Dissipators
The design of an SAF stilling basin is as shown in Section 7.6, Figure 7-3.

Step 11: Design Riprap Transition
Protection is required (See HEC 11).

Step 12: Review Results
The downstream channel conditions are matched by the dissipator.

Step 13: Documentation

Figure 7-2 : ENERGY DISSIPATOR CHECKLIST

Project No. ____

Designer ____ Date _________

Reviewer ____ Date ________

SCOUR EQUATIONS

$$\frac{d_S}{R_c}, \frac{W_S}{R_c}, \frac{L_S}{R_c} = C_S C_h \left[\frac{\alpha}{\sigma^{1/3}}\right]\left[\frac{Q}{g^{.5} R_c^{2.5}}\right]^{\beta}\left[\frac{t}{316}\right]^{\theta}$$

$$d_S, W_S, L_S = [C_S C_h \alpha/\sigma^{1/3}][DI]^{\beta}[t/316]^{\theta}\, R_c$$

$$d_S, W_S, L_S = [F_1]\,[F_2]\,[F_3]\, R_c$$

STEP 6 - DATA SUMMARY

Parameters	Culvert	Channel
Station	125+50	4+00
Control	Inlet	Super.
Type	RCB	Natural
Height, D	6 ft	7.5 ft
Width, B	7 ft	29 ft
Length, L	300 ft	—
Material	Concrete	Gravel
Manning's n	0.012	0.03 & 0.08
Side Slope	—	1:1
Discharge, Q	400 cfs	400 cfs
Depth, d	1.8 ft	2.8 ft
Velocity, V	32 ft/s	18 ft/s
$Fr = V/(gd)^{0.5}$	4.2	1.9
Flow Area, A	12.5 ft^2	22.2 ft^2
slope	0.05 ft/ft	0.05 ft/ft

STEP 7A - EQUATION INPUT DATA

FACTOR	VALUE
Q = Discharge, cfs	400 cfs
A_c= Culvert area, ft^2	42 ft^2
P_c= Perimeter, ft	26 ft
$R_c = A_c/P_c$	1.62
DI= Discharge Intensity	1.32
t = time of concentration	30 min

STEP 7B - SCOUR COMPUTATION

Factor	Depth	Width	Length
α	7.96	26.42	64.54
β	0.26	0.62	0.56
θ	0.09	0.06	0.17
F_1	0.63	0.54	0.62
F_2	8.6	31.4	75.4
F_3	0.8	0.9	0.7
$[F_1][F_2][F_3]R_c$	7	28	53
Allowable	7 ok	29 ok	60 ok

If calculate scour > Allowable and:
1. Fr > 3, design a SAF basin
2. Fr < 3, design a riprap basin
3. Fr < 3, design a USBR type VI
* These values are not standards. They may vary, depending on design criteria. In this case, calculated scour > Allowable and Fr>3: Recommend a SAF Basin.

7.5.2 Computer Output

The scour hole geometry can also be computed by using the "Energy Dissipators" module of the FHWA microcomputer program HY-8, Culvert Analysis, Version 4.0 or later. A hardcopy of the output of the module is shown below. The dimensions of the scour hole computed by the HY-8 program are in agreement with the values calculated in the previous section.

FHWA CULVERT ANALYSIS, HY-8, VERSION 6.0

CURRENT DATE	CURRENT TIME	FILE NAME	FILE DATE

CULVERT AND CHANNEL DATA

CULVERT NO. 1	DOWNSTREAM CHANNEL
CULVERT TYPE: 7.0 ft × 6.0 ft BOX	CHANNEL TYPE : IRREGULAR
CULVERT LENGTH = 300 ft	BOTTOM WIDTH = 7.0 ft
NO. OF BARRELS = 1.0	TAILWATER DEPTH = 2.8 ft
FLOW PER BARREL = 400 cfs	TOTAL DESIGN FLOW = 400.0 cfs
INVERT ELEVATION = 172.5 ft	BOTTOM ELEVATION = 172.5 ft
OUTLET VELOCITY = 31.3 ft/s	NORMAL VELOCITY = 17.5 ft/s
OUTLET DEPTH = 2.02 ft	

SCOUR HOLE GEOMETRY AND SOIL DATA

LENGTH = 91.4 ft	WIDTH = 49.3 ft
DEPTH = 9.2 ft	VOLUME = 4609.7 ft^3

MAXIMUM SCOUR OCCURS 36.6 ft DOWNSTREAM OF CULVERT

SOIL TYPE : NONCOHESIVE

SAND SIZES:
D16 = 8 mm
D50 = 14 mm
D84 = 18 mm

7.6 Riprap Aprons

7.6.1 Uses

A flat riprap apron can be used to prevent erosion at the transition from a pipe or box culvert outlet to a natural channel. Protection is provided primarily by having sufficient length and flare to dissipate energy by expanding the flow. Riprap aprons are appropriate when the culvert outlet Fr is less than or equal to 2.5. The HY-8 computer program does not include design of riprap aprons.

7.6.2 Design Procedure

The procedure presented in this section is taken from USDA, SCS (1975). Two sets of curves, one for minimum and one for maximum tailwater conditions, are used to determine the apron size and the median riprap diameter, d_{50}. If tailwater conditions are unknown, or if both minimum and maximum conditions may occur, the apron should be designed to meet criteria for both. Although the design curves are based on round pipes flowing full, they can be used for partially full pipes and box culverts. The design procedure consists of the following steps:

Step 1: If possible, determine tailwater conditions for the channel. If tailwater is less than one-half the discharge flow depth (pipe diameter if flowing full), minimum tailwater conditions exist and the curves in Figure 7-3 apply. Otherwise, maximum tailwater conditions exist and the curves in Figure 7-4 should be used.

Step 2: Determine the correct apron length and median riprap diameter, d_{50}, using the appropriate curves from Figures 7-3 and 7-4. If tailwater conditions are uncertain, find the values for both minimum and maximum conditions and size the apron as shown in Figure 7-5.

a. For pipes flowing full:

Use the depth of flow, d, which equals the pipe diameter, in feet, and design discharge, in cfs, to obtain the apron length, L_a, and median riprap diameter, d_{50}, from the appropriate curves.

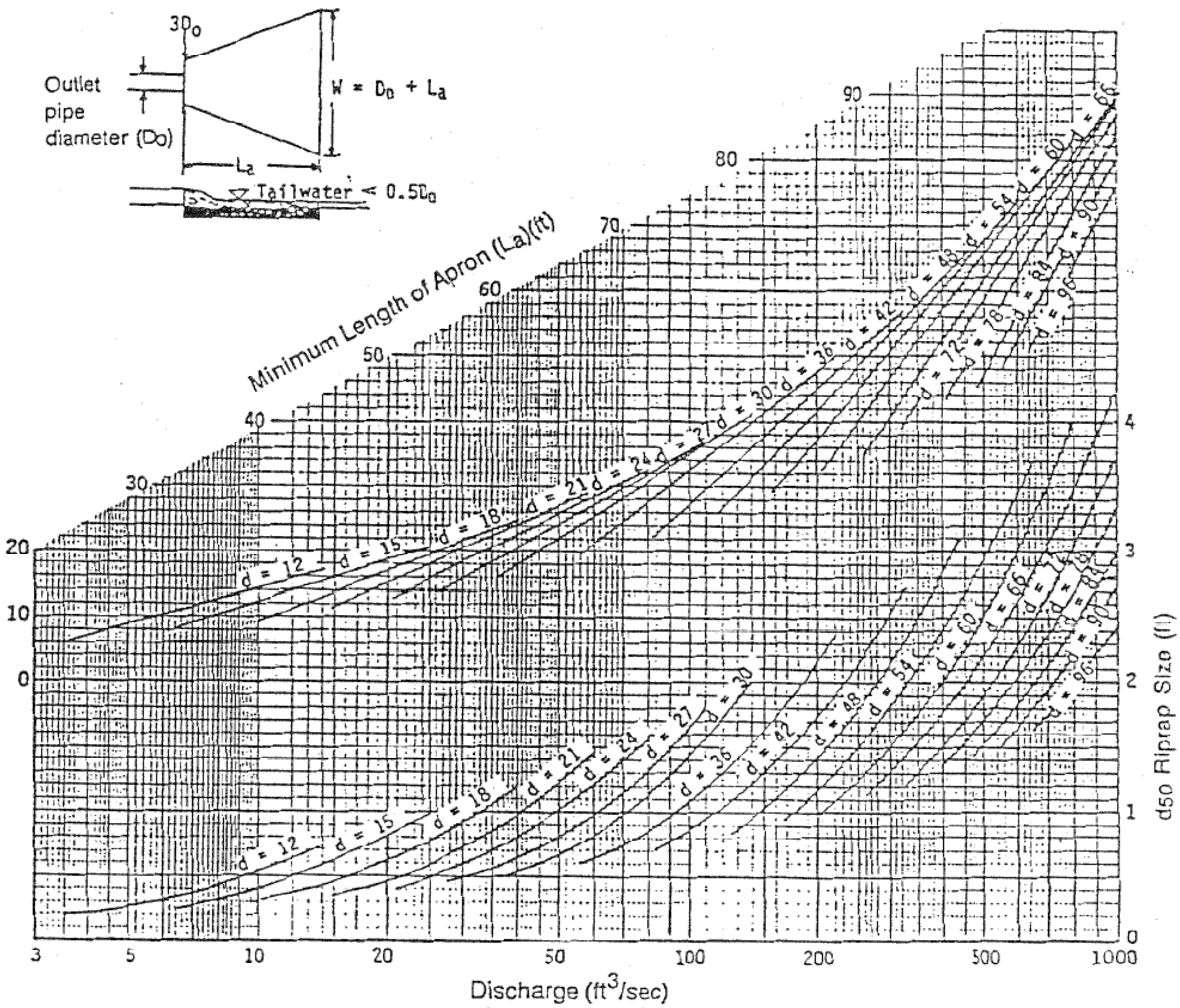
b. For pipes flowing partially full:

Use the depth of flow, d, in feet, and velocity, v, in feet/second. On the lower portion of the appropriate figure, find the intersection of the d and v curves, then find the riprap median diameter, d_{50}, from the scale on the right. From the lower d and v intersection point, move vertically to the upper curves until intersecting the curve for the correct flow depth, d. Find the minimum apron length, $L_{a,}$ from the scale on the left.

c. For box culverts:

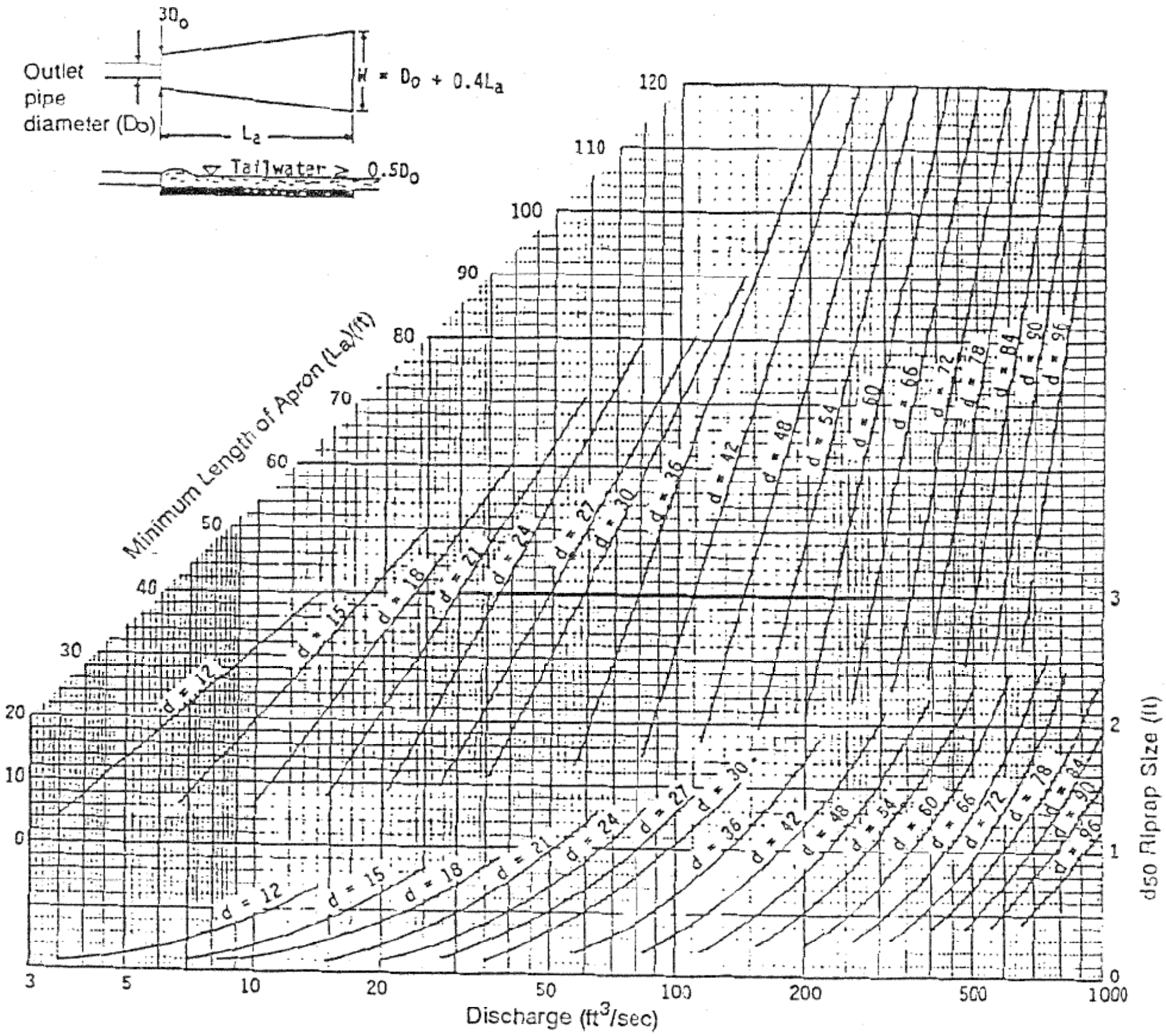
Use the depth of flow, d, in feet, and velocity, v, in feet/second. On the lower portion of the appropriate figure, find the intersection of the d and v curves, then find the riprap median diameter, d_{50}, from the scale on the right. From the lower d and v intersection point, move vertically to the upper curve until intersecting the curve equal to the flow depth, d. Find the minimum apron length, L_a, using the scale on the left.

Step 3: If tailwater conditions are uncertain, the median riprap diameter should be the larger of the values for minimum and maximum conditions. The dimensions of the apron will be as shown in Figure 7-5. This will provide protection under either of the tailwater conditions.



Curves may not be extrapolated.

Figure 7-3 Design of Riprap Apron Under Minimum Tailwater Conditions



Curves may not be extrapolated.

Figure 7-4 Design Of Riprap Apron Under Maximum Tailwater Conditions

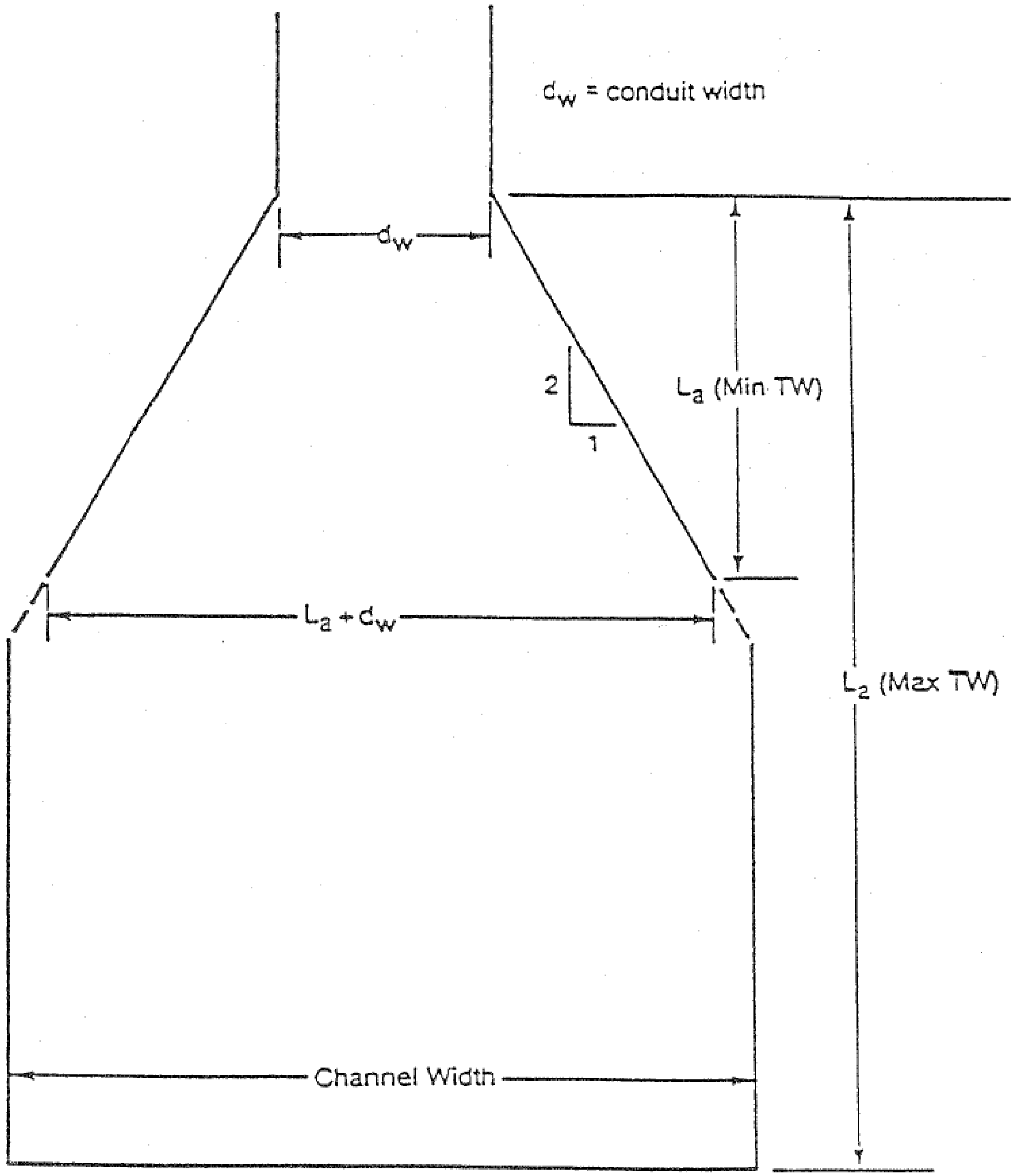


Figure 7-5 Riprap Apron Schematic For Uncertain Tailwater Conditions

7.6.3 Design Considerations

The following items should be considered during riprap apron design:

1. The maximum stone diameter should be 1.5 times the median riprap diameter.

   $d_{max} = 1.5 \times d_{50}$

   d_{50} = the median stone size in a well-graded riprap apron.

2. The riprap thickness should be 1.5 times the maximum stone diameter or 6 inches, whichever is greater.

   Apron thickness = $1.5 \times d_{max}$

   (Apron thickness may be reduced to $1.5 \times d_{50}$ when an appropriate filter fabric is used under the apron.)

3. The apron width at the discharge outlet should be at least equal to the pipe diameter or culvert width, d_w. Riprap should extend up both sides of the apron and around the end of the pipe or culvert at the discharge outlet at a maximum slope of 2:1 and a height not less than the pipe diameter or culvert height, and should taper to the flat surface at the end of the apron.

4. If there is a well-defined channel, the apron length should be extended as necessary so that the downstream apron width is equal to the channel width. The sidewalls of the channel should not be steeper than 2:1.

5. If the ground slope downstream of the apron is steep, channel erosion may occur. The apron should be extended as necessary until the slope is gentle enough to prevent further erosion.

6. The potential for vandalism should be considered if the rock is easy to carry. If vandalism is a possibility, the rock size must be increased or the rocks held in place using concrete or grout.

7.6.4 Example Problems

Example - Riprap Apron Design for Minimum Tailwater Problem Conditions

A flow of 280 cfs discharges from a 66-inch pipe with a tailwater of 2 ft above the pipe invert. Find the required design dimensions for a riprap apron.

1. Minimum tailwater conditions = $0.5\ d_o$ = 66 in = 5.5 ft, therefore, $0.5\ d_o$ = 2.75 ft.

2. Since TW = 2 ft, use Figure 7-3 for minimum tailwater conditions.

3. By Figure 7-3, the apron length, L_a, and median stone size, d_{50}, are 38 ft and 1.2 ft, respectively.

4. The downstream apron width equals the apron length plus the pipe diameter:

   $W = d + L_a = 5.5 + 38 = 43.5$ ft

5. Maximum riprap diameter is 1.5 times the median stone size:

   $1.5\ (d_{50}) = 1.5\ (1.2) = 1.8$ ft

6. Riprap depth = $1.5\ (d_{max}) = 1.5\ (1.8) = 2.7$ ft.

Example - Riprap Apron Design for Maximum Tailwater Conditions

A concrete box culvert 5.5 ft high and 10 ft wide conveys a flow of 600 cfs at a depth of 5.0 ft. Tailwater depth is 5.0 ft above the culvert outlet invert. Find the design dimensions for a riprap apron.

1. Compute 0.5 d_o = 0.5 (5.0) = 2.5 ft.

2. Since TW = 5.0 ft is greater than 2.5 ft, use Figure 7-4 for maximum tailwater conditions.

   v = Q/A = [600/(5) (10)] = 12 ft/s

3. On Figure 7-4, at the intersection of the curve, d_o = 60 in and v = 12 ft/s, d_{50} = 0.4 foot.

7.7 Riprap Basin

7.7.1 Overview

Following are the principal features of the riprap basin:

- Preshaping and lining with riprap of median size, d_{50}.
- Constructing the floor at a depth of h_S below the invert, where h_S is the depth of scour that would occur in a pad of riprap of size d_{50}.
- Sizing d_{50} so that $2 < h_S/d_{50} < 4$.
- Sizing the length of the dissipating pool to be 10(h_S) or 3(W_o), whichever is larger, for a single barrel. The overall length of the basin is 15(h_S) or 4(W_o), which ever is larger.
- Angular rock results were approximately the same as the results of rounded material.
- Layout details are shown on Figure 7-6.

<u>High Tailwater</u> ($TW/d_o > 0.75$)

- The high velocity water emerging from the culvert retains its jetlike character as it passes through the basin.
- The scour hole is not as deep as with low tailwater and is generally longer.
- Riprap may be required for the channel downstream of the rock-lined basin.

7.7.2 Design Procedure

Step 1: <u>Determine Input Flow</u>
   a. d_o or d_E, V_o, Fr at the culvert outlet (d_E = the equivalent depth at the brink = $(A/2)^{0.5}$).

Step 2: <u>Check TW</u>
   a. Determine if $TW/d_o \leq 0.75$. (See Chapter 5, Open Channels)

Step 3: <u>Determine d_{50}</u>
   a. Use Figure 7-7.
   b. Select d_{50}/d_E. Satisfactory results will be obtained if $0.25 < d_{50}/d_E < 0.45$.
   c. Obtain h_S/d_E using Froude number Fr and Figure 7-7.
   d. Check if $2 < h_S/d_{50} < 4$ and repeat until a d_{50} is found within the range.

Step 4: <u>Size Basin</u>
   a. As shown in Figure 7-6.
   b. Determine length of the dissipating pool, L_S.
      $L_S = 10h_S$ or $3W_o$ minimum.

c. Determine length of basin, L_B.
   $L_B = 15h_S$ or $4W_o$ minimum.

d. Thickness of riprap: Approach $= 3d_{50}$ or $1.5\ d_{max}$ Remainder $= 2d_{50}$ or $1.5\ d_{max}$

Step 5: Determine V_B

a. Basin exit depth, d_B = critical depth at basin exit.

b. Basin exit velocity, $V_B = Q/(W_B)(d_B)$.

c. Compare V_B with the average normal flow velocity in the natural channel, V_d.

Step 6: High Tailwater Design

a. Design a basin for low tailwater conditions, Steps 1-5.

b. Compute equivalent circular diameter D_E for brink area from:
   $A = \pi D_E^2/4 = d_o(W_o)$.

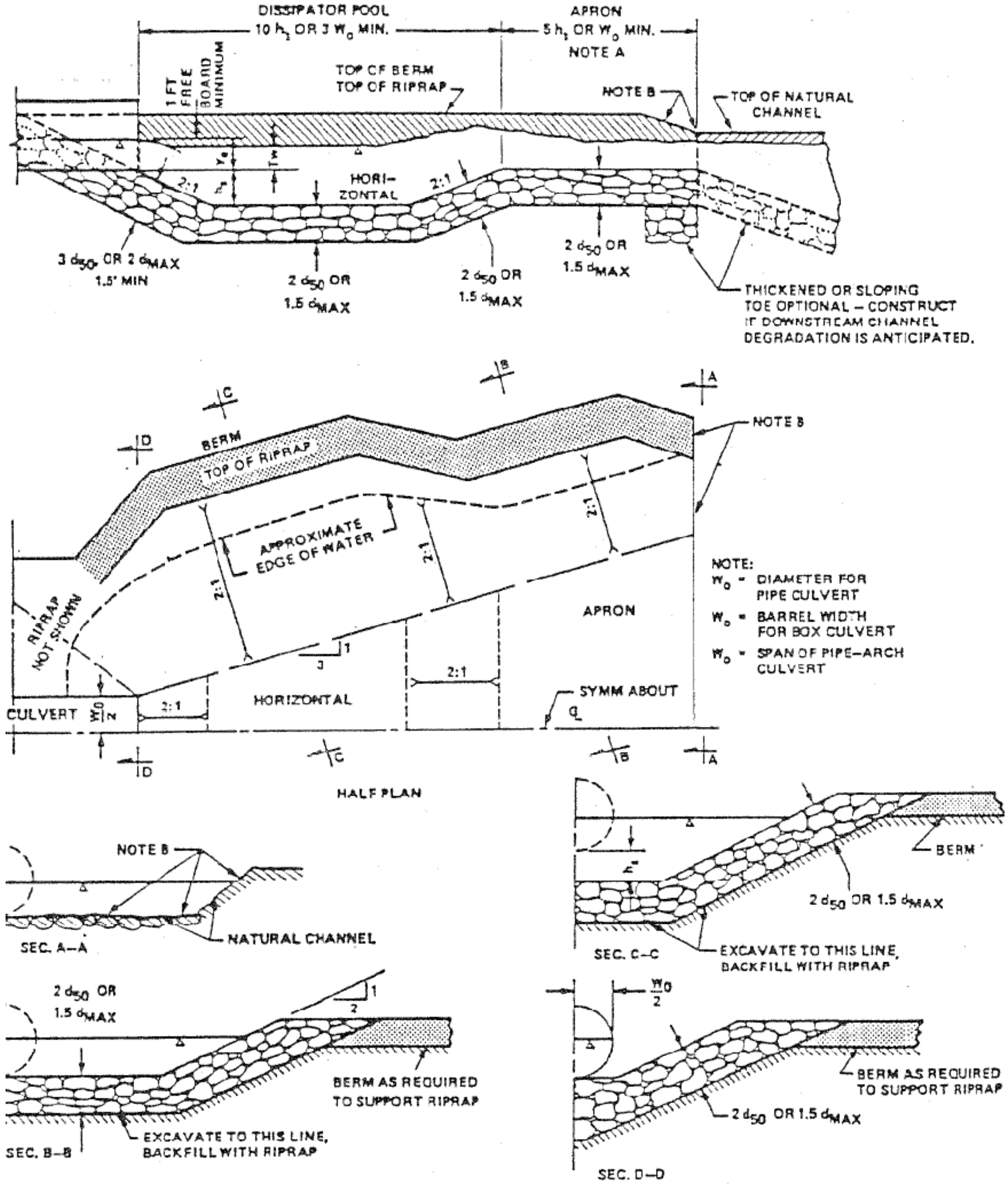
c. Estimate centerline velocity at a series of downstream cross sections using Figure 7-9.

d. Size riprap using HEC 11 "Use of Riprap For Bank Protection" or Chapter 5.

Step 7 Design Filter

a. Unless the streambed material is sufficiently well graded.

b. Follow instructions in section 4.4, HEC 11.



NOTE A – IF EXIT VELOCITY OF BASIN IS SPECIFIED, EXTEND BASIN AS REQUIRED TO OBTAIN SUFFICIENT CROSS–SECTIONAL AREA AT SECTION A–A SUCH THAT Q_{des}/(CROSS SECTION AREA AT SEC. A–A) = SPECIFIED EXIT VELOCITY.

NOTE B – WARP BASIN TO CONFORM TO NATURAL STREAM CHANNEL. TOP OF RIPRAP IN FLOOR OF BASIN SHOULD BE AT THE SAME ELEVATION OR LOWER THAN NATURAL CHANNEL BOTTOM AT SEC. A–A.

Figure 7-6 Details Of Riprap Basin Energy Dissipator

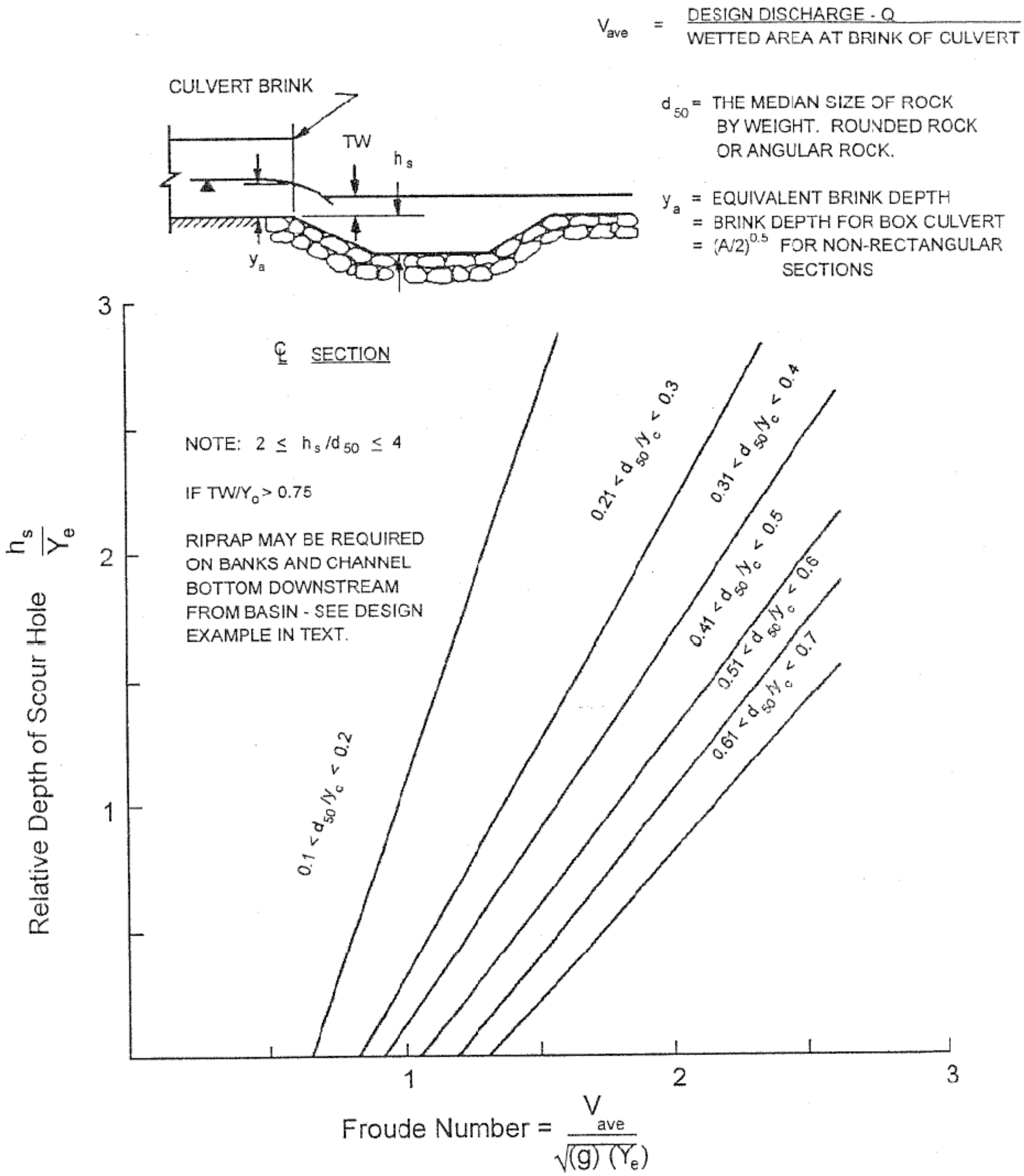
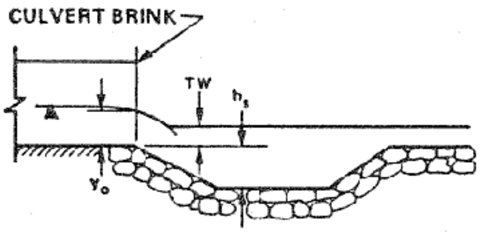
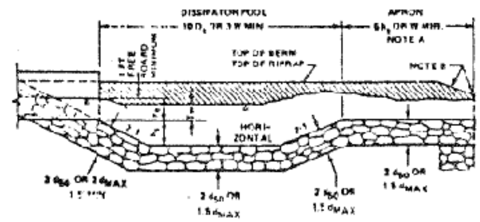


Figure 7-7 Riprap Basin Depth of Scour

RIPRAP BASIN		
PROJECT ____________	PLAN SHEET NO. ______	DATE ______
____________	DESIGNER ______	REVIEWER ______





DESIGN VALUES	TRIALS		
	1	2	3
D_{50}/d_e			
D_{50}			
F_r			
h_s/d_e			
h_s			
h_s/D_{50}			
$2 < h_s/D_{50} < 4$			

BASIN DIMENSIONS		FEET	
POOL LENGTH IS THE LARGER OF:	$10h_s$		
	$3W_o$		
BASIN LENGTH IS THE LARGER OF:	$10h_s$		
	$3W_o$		
THICKNESS APPROACH	$3D_{50}$		
THICKNESS APPROACH	$3D_{50}$		

TAILWATER CHECK	
TW	
d_e	
TW/d_e	
IF $TW/d_e > 0.75$ CALCULATE RIPRAP DOWNSTREAM USING	
$D_e=(4A_c/\pi)^{.5}$	

DOWNSTREAM RIPRAP				
L/D_e	L	V_L/V_o	V_L	D_{50}

Figure 7-8 Riprap Basin Design Checklist

7.7.3 Design Example - Low Tailwater

Low Tailwater

Box culvert — 8 ft × 6 ft
Design Discharge Q = 800 cfs
Supercritical flow in culvert
Normal flow depth d_o = brink depth d_E = 4 ft
Tailwater depth, TW = 2.8 ft

Step 1: Determine Input Flow

a. $d_o = d_E$ for rectangular section.
$d_o = d_E = 4$ ft.
$V_o = Q/A = 800/(4)8 = 25$ ft/s.
$Fr = V/(g\ d_E)^{0.5} = 25/[(32.2)4]^{0.5} = 2.20 < 3.0$, O.K.

Step 2: Check TW

a. Determine if $TW/d_o \leq 0.75$.
$TW/d_E = 2.8/4.0 = 0.7$.
Therefore $TW/d_E < 0.75$ O.K.

Step 3: Determine d_{50}

a. Use Figure 7-7.
b. Select $d_{50}/d_E = 0.45$.
$d_{50} = 0.45(4) = 1.8$ ft.
c. Obtain h_S/d_E using Fr = 2.2.
$h_S/d_E = 1.6$.
d. Check if $2 < h_S/d_{50} < 4$.
$h_S = 4(1.6) = 6.4$ ft.
$h_S/d_{50} = 6.4/1.8 = 3.6$ ft.
$2 < 3.6 < 4$, O.K.

Step 4: Size Basin

a. As shown in Figure 7-6.
b. Determine length of dissipating pool, L_S.
$L_S = 10h_S = 10(6.4) = 64$ ft,
min $= 3W_o = 3(8) = 24$ ft,
Therefore, use $L_S = 64$ ft.
c. Determine length of basin, L_B.
$L_B = 15h_S = 15(6.4) = 96$ ft,
min $= 4W_o = 4(8) = 32$ ft,
Therefore use $L_B = 96$ ft.
d. Thickness of riprap:
Approach $= 3d_{50} = 3(1.8) = 5.4$ ft,
Remainder $= 2d_{50} = 2(1.8) = 3.6$ ft.

Step 5: Determine V_B

a. d_B = critical depth at basin exit = 3.3 ft (Assuming a rectangular cross section with width $W_B = 24$ ft).
b. $V_B = Q/(W_B d_B) = 800/(24 \times 3.3) = 10$ ft/s.
c. $V_B = 10$ ft/s $< V_d = 18$ ft/s.

7.7.4 Design Example - High Tailwater

High Tailwater

Data on the channel and the culvert are the same as above except the new tailwater depth, TW = 4.2 ft.
$TW/d_o = 4.2/1.05 = 1.05 > 0.75$
Downstream channel can tolerate only 7 ft/s.

Steps 1 through 5 are the same as above.

Step 6: High Tailwater Design

a. Design a basin for low tailwater conditions, steps 1-5 as above.
$d_{50} = 1.8$ ft, $h_S = 6.4$ ft.
$L_S = 64$ ft, $L_B = 96$ ft.

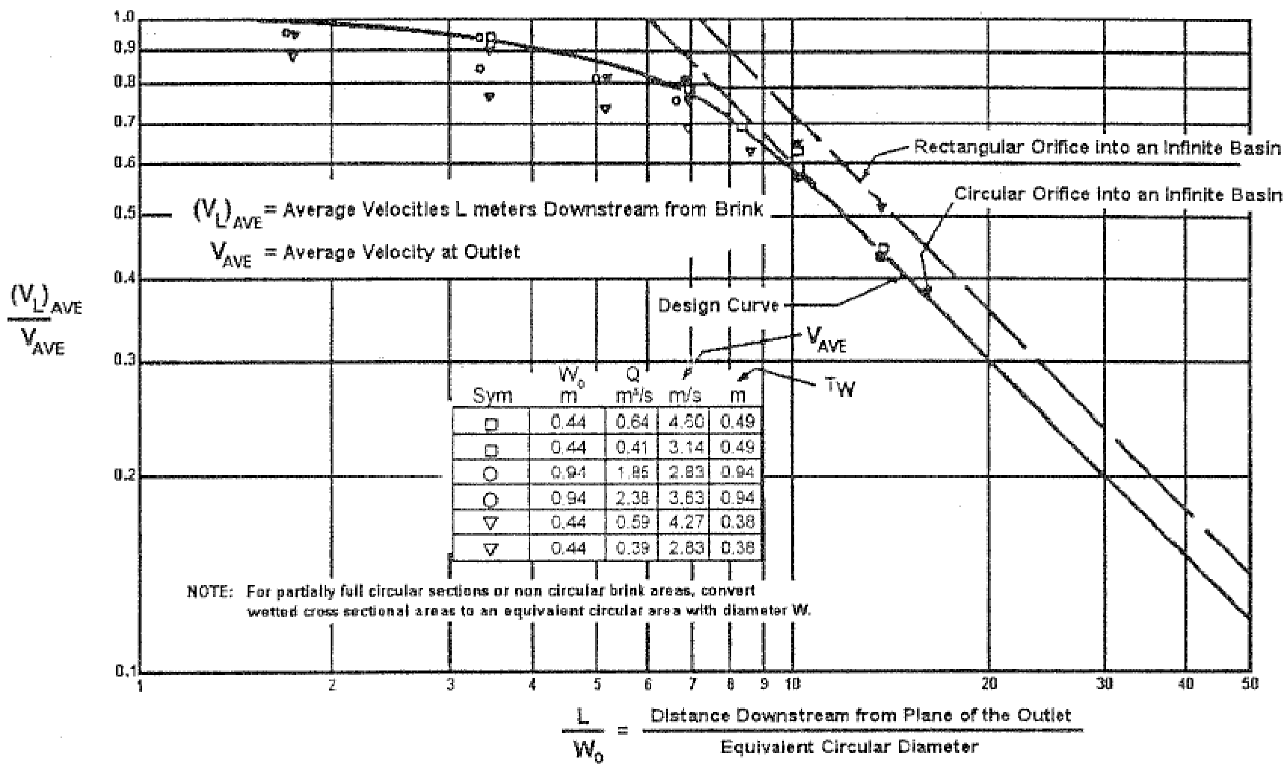
b. Compute equivalent circular diameter, D_E, for brink area from:
$A = \pi D_E^2/4 = d_o(W_o) = 4(8) = 32\ ft^2$.
$D_E = [32(4)/\pi]^{0.5} = 6.4$ ft.
$V_o = 25$ ft/s.

c. Estimate centerline velocity at a series of downstream cross sections using Figure 7-9.

L/D_E[1]	L	V_L/V_o	V_L	d_{50}[2]
10	64	0.59	14.7	1.4
15[3]	96	0.37	9.0	0.6
20	128	0.30	7.5	0.4
21	135	0.28	7.0	0.4

[1] Use $W_o = D_E$ in Figure 7-9.
[2] from Figure 7-10
[3] is on a logarithmic scale so interpolations must be made logarithmically.

d. Size riprap using HEC 11. The channel can be lined with the same size rock used for the basin. Protection must extend at least 135 ft downstream.



Note: To be used for predicting channel velocities downstream from culvert outlets where high tailwater prevails. Velocities obtained from the use of this figure can be used with HEC No. 11 for sizing riprap.

Figure 7-9 Distribution Of Centerline Velocity For Flow From Submerged Outlets

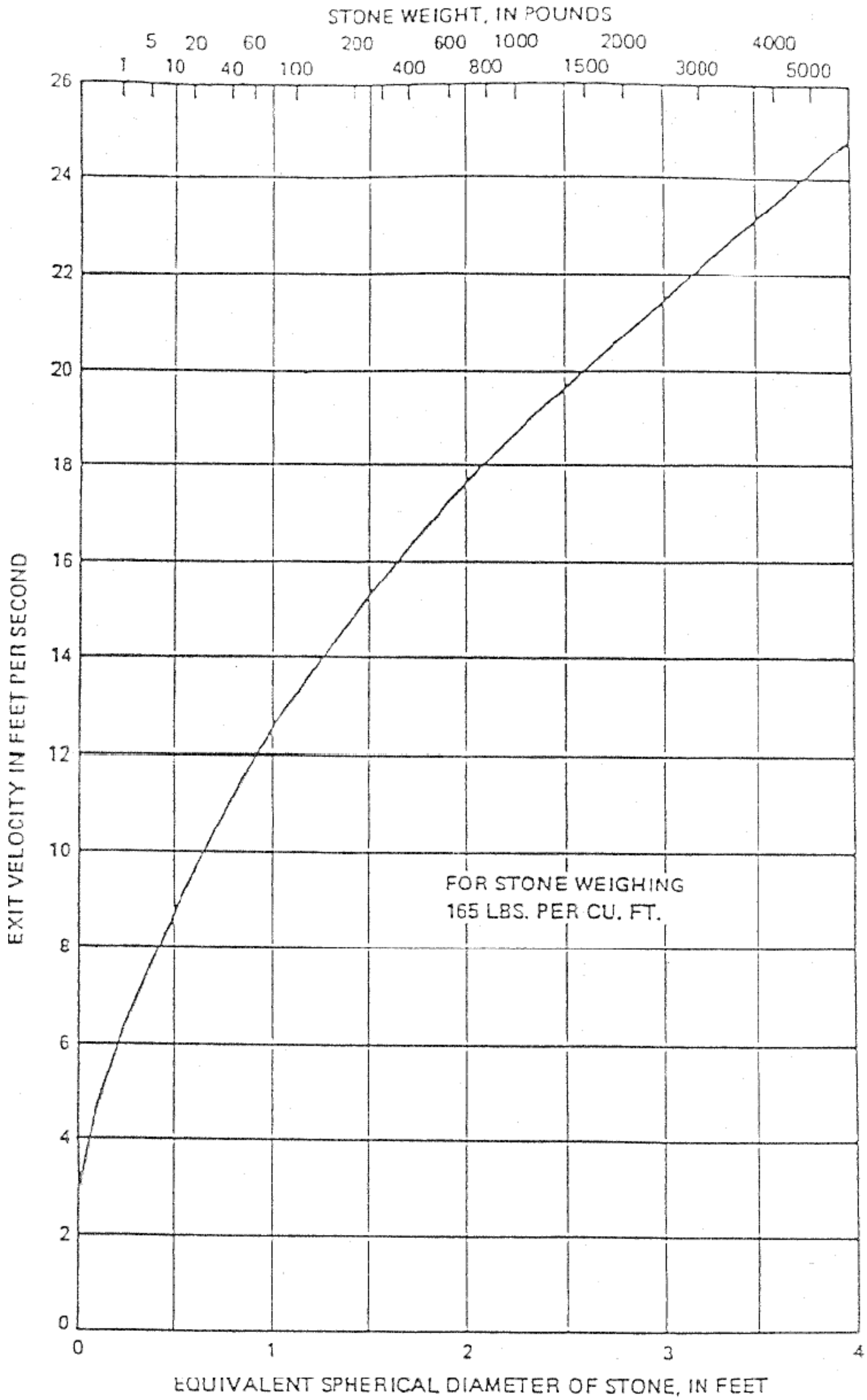
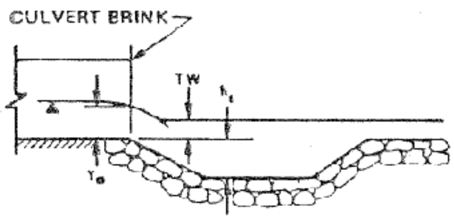
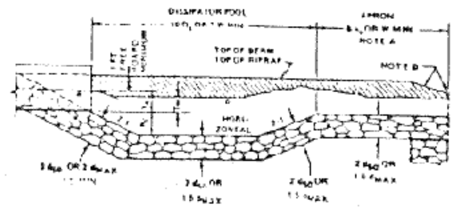


Figure 7-10 Riprap Size Versus Exit Velocity (after HEC 14)

RIPRAP BASIN		
PROJECT________	PLAN SHEET NO.______	DATE________
________	DESIGNER________	REVIEWER________





DESIGN VALUES	TRIALS		
	1	2	3
D_{50}/d_e	.45		
D_{50}	1.8'		
F_r	2.2		
h_s/d_e	1.6		
h_s	6.4'		
h_s/D_{50}	3.6'		
$2 < h_s/D_{50} < 4$	OK		

BASIN DIMENSIONS		FEET	
POOL LENGTH IS THE LARGER OF:	$10h_s$	64'	64'
	$3W_o$	24'	
BASIN LENGTH IS THE LARGER OF:	$10h_s$	96'	96'
	$3W_o$	32'	
THICKNESS APPROACH	$3D_{50}$	5.4'	
THICKNESS BASIN	$2D_{50}$	3.6'	

TAILWATER CHECK	
TW	2.8'
d_e	4.2'
TW/d_e	1.05'
IF $TW/d_e > 0.75$ CALCULATE RIPRAP DOWNSTREAM USING	
$D_e=(4A_c/\pi)^{.5}$	

DOWNSTREAM RIPRAP				
L/D_e	L	V_L/V_o	V_L	D_{50}
10	64	0.59	14.7	1.4
15	96	0.37	9.0	0.6
20	128	0.30	7.5	0.4
21	135	0.28	7.0	0.4

Figure 7-11 Riprap Basin Design Example

7.7.5 Computer Output

The dissipator geometry can be computed using the "Energy Dissipator" module which is available in microcomputer program HY-8, Culvert Analysis. The output of the culvert and channel input data, and computed geometry using this module, are shown below.

FHWA CULVERT ANALYSIS, HY-8, VERSION 4.5

CURRENT DATE CURRENT TIME FILE NAME FILE DATE

CULVERT AND CHANNEL DATA

CULVERT NO. 1	DOWNSTREAM CHANNEL
CULVERT TYPE: 8 ft × 6 ft BOX	CHANNEL TYPE : IRREGULAR
CULVERT LENGTH = 300 ft	BOTTOM WIDTH = 8.0 ft
NO. OF BARRELS = 1.0	TAILWATER DEPTH = 3.7 ft
FLOW PER BARREL = 800 cfs	TOTAL DESIGN FLOW = 800 cfs
INVERT ELEVATION = 172.5 ft	BOTTOM ELEVATION = 172.5 ft
OUTLET VELOCITY = 25 ft/s	NORMAL VELOCITY = 21.8 ft/s

RIPRAP STILLING BASIN — FINAL DESIGN

THE LENGTH OF THE BASIN	= 93.4 ft
THE LENGTH OF THE POOL	= 62.2 ft
THE LENGTH OF THE APRON	= 31.1 ft
THE WIDTH OF THE BASIN AT THE OUTLET	= 8.0 ft
THE DEPTH OF POOL BELOW CULVERT INVERT	= 6.2 ft
THE THICKNESS OF THE RIPRAP ON THE APRON	= 5.4 ft
THE THICKNESS OF THE RIPRAP ON THE REST OF THE BASIN	= 3.6 ft
THE BASIN OUTLET VELOCITY	= 10 ft/s
THE DEPTH OF FLOW AT BASIN OUTLET	= 4.4 ft

7.8 Impact Basin USBR Type VI

7.8.1 Overview

The USBR Type VI basin, Figure 7-12, developed by the U.S. Bureau of Reclamation (USBR):

- is referred to as the USBR Type VI basin or hanging baffle,
- is contained in a relatively small box-like structure,
- requires no tailwater for successful performance,
- may be used in open channels, as well, and
- is not recommended where debris or ice buildup may cause substantial clogging.

Hanging Baffle

Energy dissipation is initiated by flow striking the vertical hanging baffle and being deflected upstream by the horizontal portion of the baffle and by the floor, creating horizontal eddies.

Notches in Baffle

Notches are provided to aid in cleaning the basin. The notches provide concentrated jets of water for cleaning. The basin is designed to carry the full discharge over the top of the baffle if the space beneath the baffle becomes completely clogged.

Equivalent Depth

This depth must be calculated for a pipe or irregular shaped conduit. The cross section flow area in the pipe is converted into an equivalent rectangular cross section in which the width is twice the depth of flow.

Limitations

Discharges up to 400 cfs per barrel and velocities as high as 50 ft/s can be used without subjecting the structure to cavitation damage.

Tailwater

A moderate depth of tailwater will improve performance. For best performance, set the basin so that maximum tailwater does not exceed $h_3 + (h_2/2)$.

Slope

If culvert slope is greater than 15°, a horizontal section of at least four culvert widths should be provided upstream.

End Treatment

An end sill with a low-flow drainage slot, 45° wingwalls and a cutoff wall should be provided at the end of the basin.

Riprap

Riprap should be placed downstream of the basin for a length of at least four conduit widths.

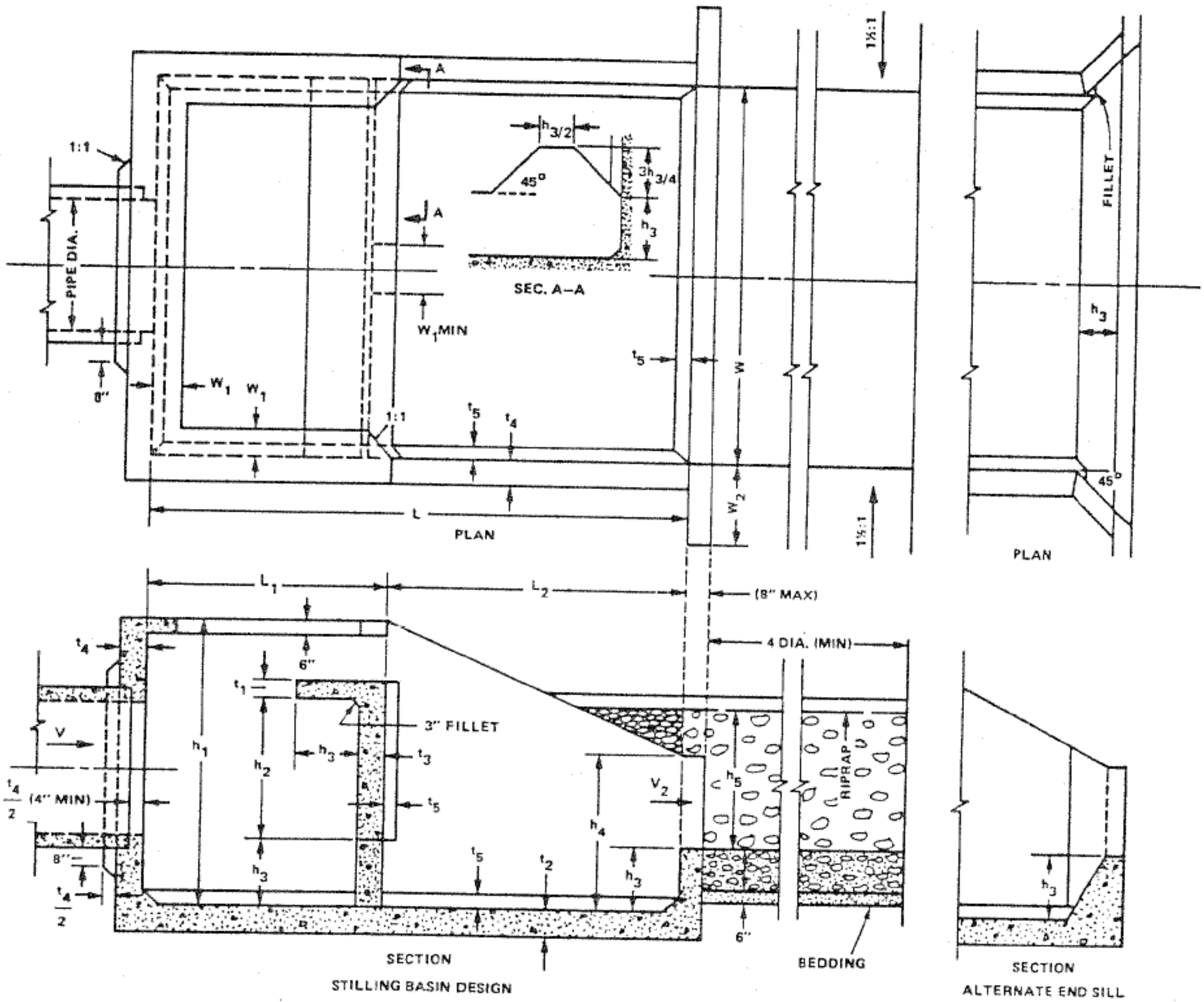


Figure 7-12 USBR Type VI (Impact) Dissipator

7.8.2 Design Procedure

Step 1: Calculate equivalent depth, d_E
- a. Rectangular section, $d_E = d_o = y_o$.
- b. Other sections, $d_E = (A/2)^{0.5}$.

Step 2: Determine Input Flow
- a. Froude number, $Fr = V_o/(gd_E)^{0.5}$.
- b. Specific energy, $H_o = d_E + V_o^2/2g$.

Step 3: Determine Basin Width, W
- a. Use Figure 7-15.
- b. Enter with Fr and read H_o/W.
- c. $W = H_o/(H_o/W)$.

Step 4: Size Basin
- a. Use Table 7-3 and W.
- b. Obtain the remaining dimensions.

Step 5: Energy Loss
- :a. Use Figure 7-14.
- b. Enter with Fr and read H_L/H_o.
- c. $H_L = (H_L/H_o)H_o$.

Step 6: Exit Velocity (V_B)
- a. Exit energy (H_E) = $H_o - H_L$.
- b. $H_E = d_B + V_B^2/2g$.
  $V_B = (Q/W)/d_B$.

7.8.3 Design Example

Inputs

$D = 48$ inch pipe, $S_o = 0.15$ ft/ft, $n = 0.015$.
$Q = 300$ cfs, $d_o = 2.3$ ft, $V_o = 40$ ft/s.

Step 1: Calculate equivalent depth, d_E.
- b. Other sections, $d_E = (A/2)^{0.5}$.
  $A = Q/V_o = 300/40 = 7.5\ ft^2$.
  $d_E = (7.5/2)^{0.5} = 1.94$ ft.

Step 2: Determine Input Flow
- a. Froude number, $Fr_o = V_o/(gd_E)^{0.5}$.
  $Fr = 40/[32.2(1.94)]^{0.5} = 5.05$.
- b. Specific energy, $H_o = d_E + V_o^2/2g$.
  $H_o = 1.94 + (40)^2/(2)(32.2) = 26.8$ ft.

Step 3: Determine basin width, W.
- a. Use Figure 7-15.
- b. Enter with Fr = 5.05 and read $H_o/W = 1.68$.
- c. $W = H_o/(H_o/W) = 26.8/1.68 = 16$ ft.

Table 7-3 Dimensions Of USBR Type VI Basin

(Dimensions, ft)
(See Figure 7-12)

W	h_1	h_2	h_3	h_4	L	L_1	L_2
4	3-1	1-6	0-8	1-8	5-5	2-4	3-1
5	3-10	1-11	0-10	2-1	6-8	2-11	3-10
6	4-7	2-3	1-0	2-6	8-0	3-5	4-7
7	5-5	2-7	1-2	2-11	9-5	4-0	5-5
8	6-2	3-0	1-4	3-4	10-8	4-7	6-2
9	6-11	3-5	1-6	3-9	12-0	5-2	6-11
10	7-8	3-9	1-8	4-2	13-5	5-9	7-8
11	8-5	4-2	1-10	4-7	14-7	6-4	8-5
12	9-2	4-6	2-0	5-0	16-0	6-10	9-2
13	10-2	4-11	2-2	5-5	17-4	7-5	10-0
14	10-9	5-3	2-4	5-10	18-8	8-0	10-9
15	11-6	5-7	2-6	6-3	20-0	8-6	11-6
16	12-3	6-0	2-8	6-8	21-4	9-1	12-3
17	13-0	6-4	2-10	7-1	21-6	9-8	13-0
18	13-9	6-8	3-0	7-6	23-11	10-3	13-9
19	14-7	7-1	3-2	7-11	25-4	10-10	14-7
20	15-4	7-6	3-4	8-4	26-7	11-5	15-4

W	W_1	W_2	t_1	t_2	t_3	t_4	t_5
4	0-4	1-1	0-6	0-6	0-6	0-6	0-3
5	0-5	1-5	0-6	0-6	0-6	0-6	0-3
6	0-6	1-8	0-6	0-6	0-6	0-6	0-3
7	0-6	1-11	0-6	0-6	0-6	0-6	0-3
8	0-7	2-2	0-6	0-7	0-7	0-6	0-3
9	0-8	2-6	0-7	0-7	0-8	0-7	0-3
10	0-9	2-9	0-8	0-8	0-9	0-8	0-3
11	0-10	3-0	0-8	0-9	0-9	0-8	0-4
12	0-11	3-0	0-8	0-10	0-10	0-9	0-4
13	1-0	3-0	0-8	0-11	0-10	0-10	0-4
14	1-1	3-0	0-8	1-0	0-11	0-11	0-5
15	1-2	3-0	0-8	1-0	1-0	1-0	0-5
16	1-3	3-0	0-9	1-0	1-0	1-0	0-6
17	1-4	3-0	0-9	1-1	1-0	1-0	0-6
18	1-4	3-0	0-9	1-1	1-1	1-1	0-7
19	1-5	3-0	0-10	1-2	1-1	1-1	0-7
20	1-6	3-0	0-10	1-2	1-2	1-2	0-8

Step 4: <u>Size Basin</u>

a. Use Table 7-3 and W.

b. Obtain the remaining dimensions.

Step 5: <u>Energy Loss</u>

a. Use Figure 7-14.

b. Enter with Fr = 5.05 and read $H_L/H_o = 0.67$.

c. $H_L = (H_L/H_o)H_o = 0.67(26.8) = 18$ ft.

Step 6: <u>Exit Velocity</u> (V_B)

a. Exit energy (H_E) = $H_o - H_L = 26.8 - 18 = 8.8$ ft.

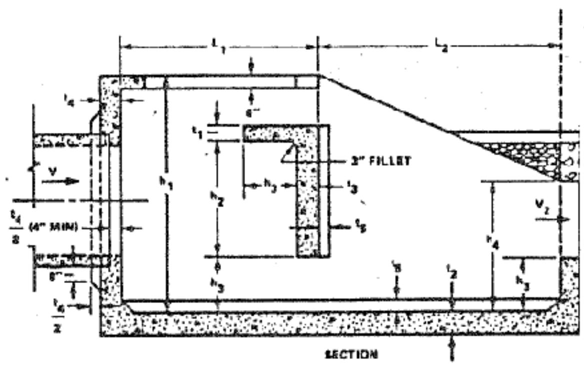
b. $H_E = d_B + V_B^2/2g = 8.8$ ft.
$V_B = (Q/W)/d_B = (300/16)/d_B = 18.75/d_B$.

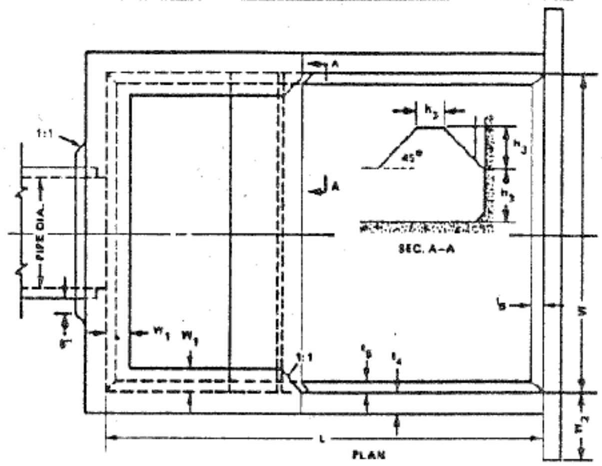
d_B	V_B	$d_B+V_B^2/2g = 2.69$
$2.3 = d_o$	8.1	3.3
1.0	18.8	6.5
0.8	23.4	9.3, use
0.9	20.8	7.6

USBR TYPE VI DISSIPATOR COMPUTATION FORM

PROJECT____________________________ PLAN SHEET NO._____ DATE____________

__________________________________ DESIGNER__________ REVIEWER__________





CHOOSE BASIN WIDTH (W)	TRIALS		
	1	2	3
$d_e = y_e$			
V_o			
$H_o = d_e + V_o^2/2g$			
F_r			
H_o/W			
$W = H_o/(H_o/W)$			

CHECK OUTLET VELOCITY (V_B)			
H_L/H_o			
$H_L = (H_L/H_o)H_o$			
$H_e = H_o - H_L$			
d_B			
$V_B = (Q/W)/d_B$			
$(H_e)_T = d_B + V_B^2/2g$			
IF $(H_e)_T \neq H_e$ CHOOSE ANOTHER D_B			

BASIN DIMENSIONS (FEET-INCHES)							
W	h_1	h_2	h_3	h_4	L	L_1	L_2
W	W_1	W_2	t_1	t_2	t_3	t_4	t_5

Figure 7-13 Impact Basin Type VI Checklist

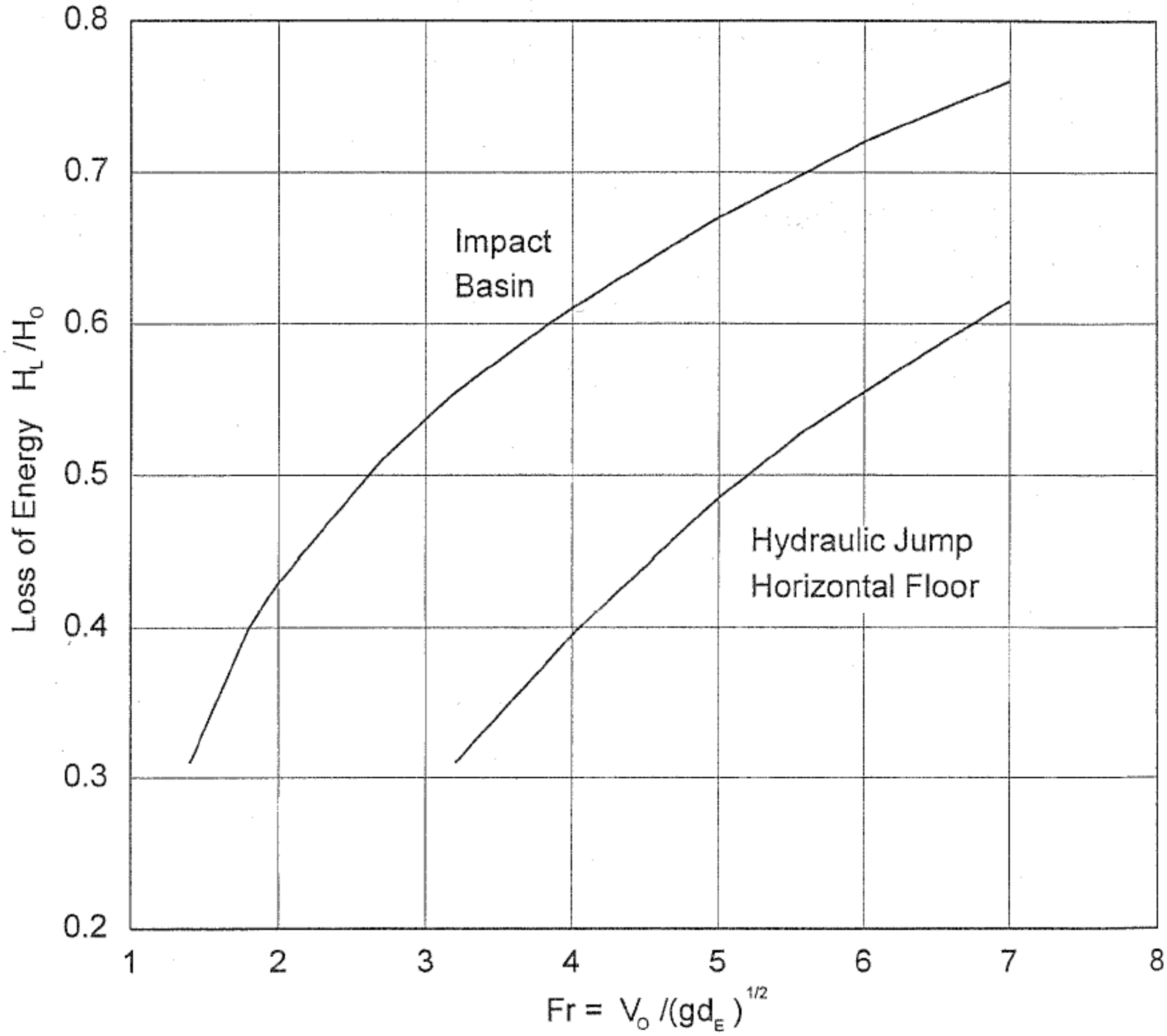


Figure 7-14 Energy Loss For USBR Type VI Dissipator

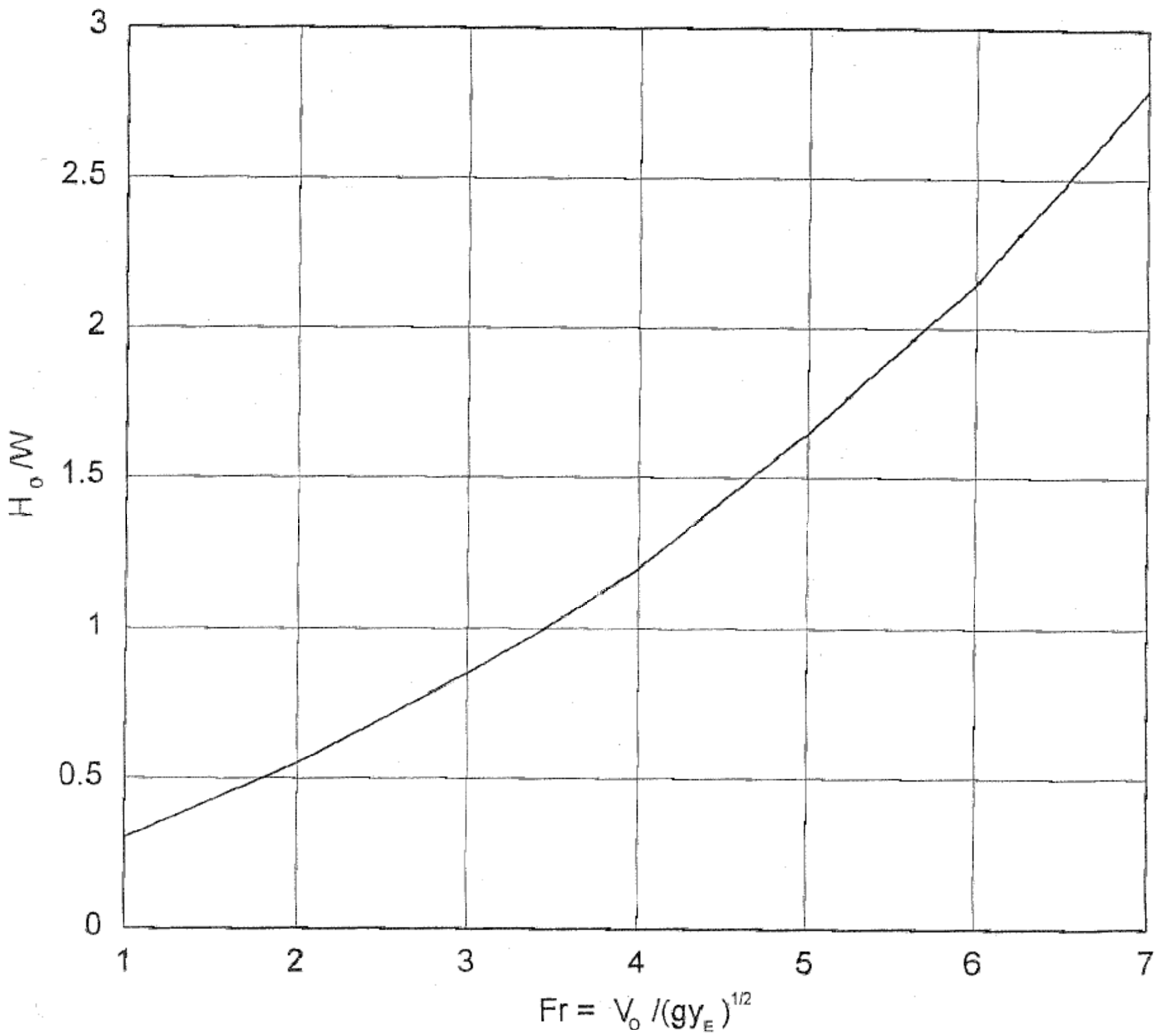
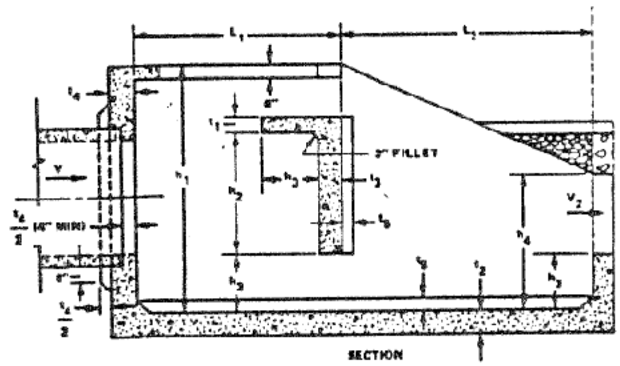
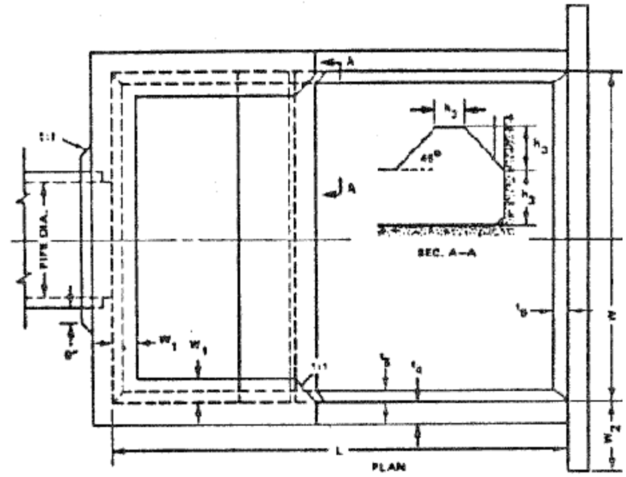


Figure 7-15 Design Curve For USBR Type VI Dissipator

USBR TYPE VI DISSIPATOR COMPUTATION FORM		
PROJECT______________________	PLAN SHEET NO._____	DATE__________
______________________	DESIGNER__________	REVIEWER__________





CHOOSE BASIN WIDTH (W)	TRIALS		
	1	2	3
$d_e=y_e=d_o$	2.3'		
V_o	40		
$H_o=d_e+V_o2/2g$	26.8'		
F_r	5.1		
H_o/W	1.68		
$W=H_o/(H_o/W)$	16'		

CHECK OUTLET VELOCITY (V_B)			
H_L/H_o	.67		
$H_L=(H_L/H_o)H_o$	18'		
$H_e=H_o-H_L$	8.8'		
d_B	2.3'	0.9'	0.8'
$V_B=(Q/W)/d_B$	8.1	20.8	23.4
$(H_e)_T=d_B+V_B2/2g$	3.3'	7.6'	9.3'
IF $(H_e)_T \neq H_e$ CHOOSE ANOTHER D_B			

BASIN DIMENSIONS (FEET-INCHES)							
W	h_1	h_2	h_3	h_4	L	L_1	L_2
16	12-3	6-0	2-8	6-8	21-4	9-1	12-3
W	W_1	W_2	t_1	t_2	t_3	t_4	t_5
16	1-3	3-0	0-9	1-0	1-0	1-0	0-6

Figure 7-16 USBR Basin Type VI - Design Example

7.8.4 Computer Output

The dissipator geometry can be computed using the "Energy Dissipator" module which is available in microcomputer program HY-8, Culvert Analysis. The output of the culvert and channel input data, and computed geometry using this module are shown below.

FHWA CULVERT ANALYSIS, HY-8, VERSION 4.5

CURRENT DATE	CURRENT TIME	FILE NAME	FILE DATE

CULVERT AND CHANNEL DATA

CULVERT NO. 1	DOWNSTREAM CHANNEL
CULVERT TYPE: 4 ft CIRCULAR	CHANNEL TYPE : IRREGULAR
CULVERT LENGTH = 300 ft	BOTTOM WIDTH = 7 ft
NO. OF BARRELS = 1.0	TAILWATER DEPTH = 2.5 ft
FLOW PER BARREL = 300 cfs	TOTAL DESIGN FLOW = 300 cfs
INVERT ELEVATION = 172.5 ft	BOTTOM ELEVATION = 172.5 ft
OUTLET VELOCITY = 4.0 ft/s	NORMAL VELOCITY = 15.9 ft/s

USBR TYPE 6 DISSIPATOR — FINAL DESIGN

BASIN OUTLET VELOCITY = 2.1 ft/s

W = 16 ft	W1 = 1.3 ft	W2 = 3.0 ft
L = 21.3 ft	L1 = 9.1 ft	L2 = 12.3 ft
H1 = 12.3 ft	H2 = 6.0 ft	H3 = 2.7 ft
H4 = 6.7 ft	T1 = 0.8 ft	T2 = 1.0 ft
T3 = 1.0 ft	T4 = 1.0 ft	T5 = 0.5 ft

7.9 SAF Stilling Basin

7.9.1 Overview

The St. Anthony Falls (SAF) stilling basin uses a forced hydraulic jump to dissipate energy and:

- is based on model studies conducted by US Soil Conservation Service (SCS) at the St. Anthony Falls (SAF) Hydraulic Laboratory of the University of Minnesota;
- uses chute blocks, baffle blocks and an end sill to force the hydraulic jump and reduce jump length by about 80%;
- is recommended where Fr = 1.7 to 17.

7.9.2 Equations

Basin Width, W_B

- for box culvert W_B = B = Culvert width, ft
- for pipe, use W_B = Culvert diameter, D, ft, or

$$W_B = \frac{0.03Q}{D^{1.5}} \quad (7.7)$$

whichever is larger.

Where: Q = discharge, cfs

Flare (z:1)

Flare is optional, if used it should be flatter than 2:1.

Basin Length, L_B

$$d_j = \frac{d_1}{2}[(1 + 8Fr_1^2)^{0.5} - 1] \quad (7.8)$$

Where: d_1 = initial depth of water, ft
d_j = sequent depth of jump, ft
Fr_1 = Froude number entering basin, $\neq$ Fr

$$L_B = \frac{4.5d_j}{Fr_1^{0.76}} \quad (7.9)$$

Basin Floor

The basin floor should be depressed below the streambed enough to obtain the following depth (d_2) below the tailwater:

- For Fr_1 = 1.7 to 5.5

$$d_2 = d_j[1.1 - (\frac{Fr_1^2}{120})] \tag{7.10}$$

- For Fr_1 = 5.5 to 11

$$d_2 = 0.85d_j \tag{7.11}$$

- For Fr_1 = 11 to 17

$$d_2 = d_j[1.1 - (\frac{Fr_1^2}{800})] \tag{7.12}$$

Chute Blocks

Height, $h_1 = d_1$
Width, W_1 = Spacing, $W_1 = 0.75d_1$
Number of blocks = $N_c = W_B/2W_1$, rounded to a whole number
Adjusted $W_1 = W_2 = W_B/2N_c$
N_c includes the ½ block at each wall

Baffle Blocks

Height, $h_3 = d_1$
Width, W_3 = Spacing, $W_4 = 0.75d_1$
Basin width at baffle blocks, $W_{B2} = W_B + 2L_B/3z$
Number of blocks = $N_B = W_{B2}/2W_3$, rounded to a whole number
Adjusted $W_3 = W_4 = W_{B2}/2N_B$
Check total block width to insure that 40 to 55% of W_{B2} is occupied by block.
Staggered with chute blocks
Space at wall $\geq 0.38d_1$
Distance from chute blocks (L_{1-3}) = $L_B/3$

End Sill Height, $h_4 = 0.07d_j$
Sidewall Height = $d_2 + 0.33d_j$
Wingwall Flare = 45°

7.9.3 Design Procedure

The design of a St. Anthony Falls (SAF) basin consists of several steps as follows:

Step: 1 Select Basin Type
  a. Rectangular or flared.
  b. Choose flare (if needed), z:1.
  b. Determine basin width, W_B.

Step: 2 Select Depression
  a. Choose the depth d_2 to depress below the streambed, B_d.
  b. Assume $B_d = 0$ for first trial.

Step 3: Determine Input Flow

a. d_1 and V_1, using energy equation.
b. Froude Number, Fr_1.

Step 4: Calculate Basin Dimensions
a. d_j (equation 7.8).
b. L_B (equation 7.9).
c. d_2 (equation 7.10, 7.11, or 7.12).
d. $L_S = (d_2 - TW)/S_S$
e. $L_T = (B_d)/S_T$ (see Figure 7-3).
f. $L = L_T + L_B + L_S$ (see Figure 7-3).

Step 5: Review Results
a. If $d_2 \neq (B_d - LS_o + TW)$ return to Step 2.
b. If approximately equal, continue.

Step 6: Size Elements
a. Chute blocks (h_1, W_1, W_2, N_c).
b. Baffle blocks (h_3, W_3, W_4, N_B, $L_{1\text{-}3}$).
c. End sill (h_4).
d. Side wall height ($h_5 = d_2 + 0.33d_j$).

7.9.4 Design Example

- See Figure 7-18 for completed computation form.

Step 1: Select Basin Type
a. Use rectangular with no flare
b. Basin width, $W_B = 7$ ft

Step 2: Select Depression
Trial 1 $B_d = 8$ ft, $S_S = S_t = 1$

Step 3: Determine Input Flow
Trial 1 a. Energy equation (culvert to basin):
Culvert outlet $= B_d + d_o + V_o^2/2g = 8 + 1.8 + (32)^2/2(32.2) = 25.7$ ft
Basin floor $= 0 + d_1 + V_1^2/2g$
Solve: $25.7 = d_1 + V_1^2/2g$

d_1	V_1	$d_1+V_1^2/2g$
1.5	38	24 < 25.4
1.4	41	27.5 > 25.7, Use:

b. $Fr_1 = 41/(1.4 \times 32.2)^{0.5} = 6.1$.

Step 4: Calculate Basin Dimensions
Trial 1
a. $d_j = 11.4$ ft (equation 7.8).
b. $L_B = 13.0$ ft (equation 7.9).
c. $d_2 = 9.7$ ft (equation 7.10).
d. $L_S = (d_2 - TW)/S_S = (9.7 - 2.8)/1 = 6.9$ ft.
e. $L_T = (B_d)/S_T = 8/1 = 8$ ft.
f. $L = L_T + L_B + L_S = 8 + 13 + 7 = 28$ ft.

Step 5: Review Results
Trial 1

a. If d_2 does not equal (B_d - LS_o + TW), then adjust drop
$9.7 \neq (8 - 28(0.05) + 2.8) = 9.4$ ft.
b. Add 9.7 - 9.4 = 0.3 more drop and return to Step 2.

Step 2: Select Depression
Trial 2

$B_d = 8.3$ ft, $S_S = S_T = 1$

Step 3: Determine Input Flow
Trial 2

a. Energy equation (culvert to basin):
Culvert outlet = $B_d + d_o + V_o^2/2g = 8.3 + 1.8 + (32)^2/2g = 26.0$ ft
Basin floor = $0 + d_1 + V_1^2/2g$
Solve: $26.0 = d_1 + V_1^2/2g$

d_1	V_1	$d_1 + V_1^2/2g$
1.4	41	27.5 > 26.0, Use:

b. $Fr_1 = 41/(1.4 \times 32.2)^{0.5} = 6.1$.

Step 4: Calculate Basin Dimensions
Trial 2

a. $d_j = 11.4$ ft (equation 7.8).
b. $L_B = 13.0$ ft (equation 7.9).
c. $d_2 = 9.7$ ft (equation 7.10).
d. $L_S = (d_2 - TW)/S_S = (9.7 - 2.8)/1 = 6.9$ ft.
e. $L_T = (B_d)/S_T = 8.3/1 = 8.3$ ft.
f. $L = L_T + L_B + L_S = 8.3 + 13 + 7 = 28.3$ ft

Step 5: Review Results
Trial 2

b. $d_2 = 9.7 = (8.3 - 28.3(0.05) + 2.8) = 9.7$ ft. Is equal, continue.

Step 6: Size Elements
Trial 2

a. Chute blocks (h_1, W_1, W_2, N_c)
$h_1 = d_1 = 1.4$ ft.
$W_1 = 0.75d_1 = 1$ ft.
$N_c = W_B/2(W_1) = 7/2(1) = 3.5$, use 4.
Adjusted $W_1 = 7/2(4) = 0.9$ ft $= W_2$.
Use 6 full blocks, 4 spaces and a half of block at each wall.
b. Baffle blocks (h_3, W_3, W_4, N_B, L_{1-3})
$h_3 = d_1 = 1.4$ ft.
$W_3 = 0.75d_1 = 1$ ft.
Use 4 blocks, and adjusted as above $W_3 = W_4 = 0.9$ ft.
$L_{1-3} = L_B/3 = 13/3 = 4.3$ ft.
c. End sill (h_4) $= 0.07d_j = 0.07(11.4) = 0.8$ ft.
d. Side wall height (h_5) $= d_2 + 0.33d_j = 9.7 + 0.33(11.4) = 13.5$ ft.

Figure 7-17 : ST. ANTHONY FALLS (SAF) BASIN

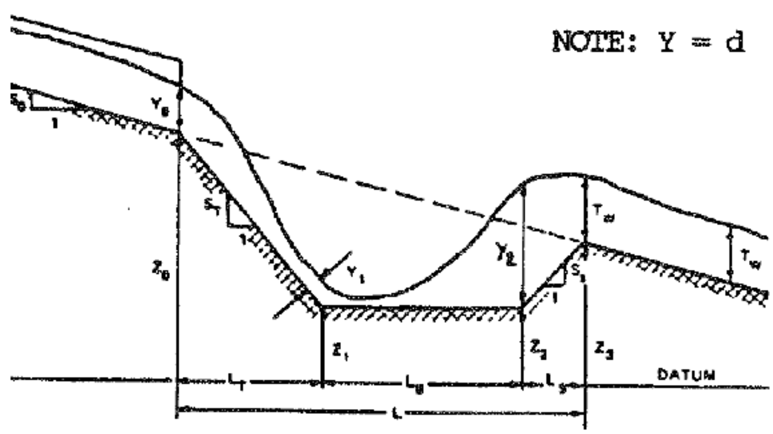
Project No. ____

Designer ____ Date ________

Reviewer ____ Date ________

SAF BASIN DESIGN VALUES	TRIAL 1	FINAL TRIAL
Type		
Flare (z:1)		
Width, W_B		
Depression, B_d		
$S_S = S_T$		
Depth, d_o		
Velocity, V_o		
$B_o = d_o + V_o^2/2g$		
Depth, d_1		
Velocity, V_1		
Fr_1		
d_j		
L_B		
d_2		
L_S		
$L_T = B_d / S_T$		
$L = L_B + L_S + L_T$		
$B_d = LS_o + TW$		

DIMENSIONS OF ELEMENTS	TRIAL 1	FINAL TRIAL	DIMENSIONS OF ELEMENTS	TRIAL 1	FINAL TRIAL
CHUTE BLOCK			BAFFLE BLOCK		
Height, h_1			Height, h_3		
Width, W_1			Width, W_3		
Spacing, W_2			Spacing, W_4		
Block No., N_C			Block No., N_B		
END SILL			SIDE WALL		
Height, h_4			Height, h_5		



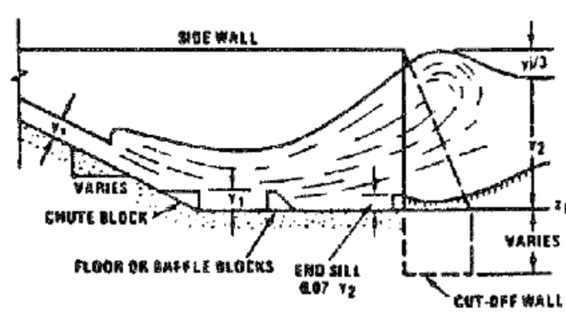


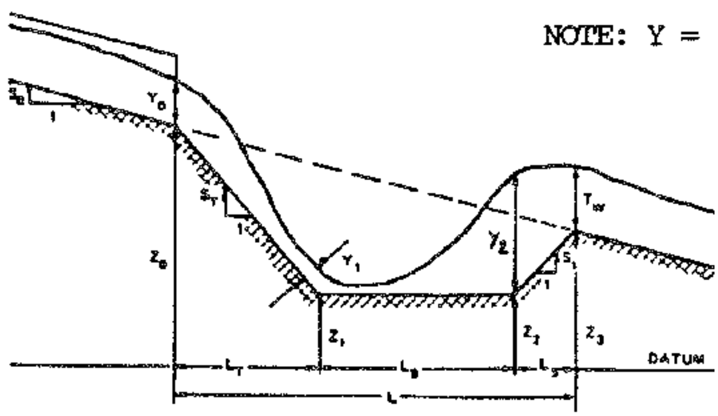
Figure 7-17 St. Anthony Falls Basin Checklist

Figure 7-18: ST. ANTHONY FALLS (SAF) BASIN

Project No. Example Problem
Designer ______________________ Date ________
Reviewer ______________________ Date ________

SAF BASIN DESIGN VALUES	TRIAL 1	FINAL TRIAL
Type	Rect.	Rect.
Flare (Z:1)	1:1	1:1
Width, W_B	7	7
Depression, B_d	8	8.3
$S_S = S_T$	1:1	1:1
Depth, d_o	1.8	1.8
Velocity, V_o	32	32
$B_o = d_o + V_o^2/2g$	25.7	26.0
Depth, d_1	1.4	1.4
Velocity, V_1	41	41
Fr_1	6.1	6.1
d_j	11.4	11.4
L_B	13	13
d_2	9.7	9.7
L_S	6.9	7.0
$L_T = B_d / S_T$	8	8.3
$L = L_B + L_S + L_T$	28	28.3
$B_d - LS_o + TW$	9.4	9.7

DIMENSIONS OF ELEMENTS	TRIAL 1	FINAL TRIAL	DIMENSIONS OF ELEMENTS	TRIAL 1	FINAL TRIAL
CHUTE BLOCK			BAFFLE BLOCK		
Height, h_1	1.4	1.4	Height, h_3	1.4	1.4
Width, W_1	1	0.9	Width, W_3	1	0.9
Spacing, W_2	0.9	0.9	Spacing, W_4	1	0.9
Block No., N_C	4	4	Block No., N_B	4	4
END SILL			SIDE WALL		
Height, h_4	0.8	0.8	Height, h_5	13.5	13.5



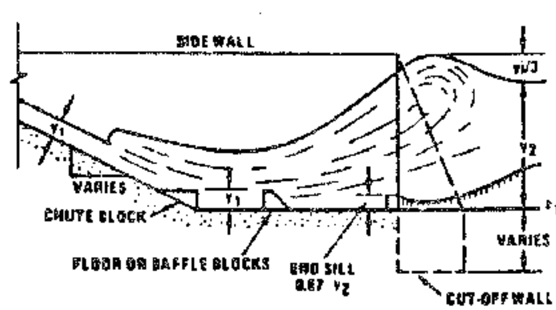


Figure 7-18 St. Anthony Falls Basin Example Problem

7.9.5 Computer Output

The dissipator geometry can be computed using the "Energy Dissipator" module which is available in microcomputer program HY-8, Culvert Analysis. The output of the culvert and channel input data, and computed geometry using this module are shown below.

FHWA CULVERT ANALYSIS, HY-8, VERSION 6.0

CURRENT DATE	CURRENT TIME	FILE NAME	FILE DATE

CULVERT AND CHANNEL DATA

CULVERT NO. 1	DOWNSTREAM CHANNEL
CULVERT TYPE: 7.0 ft × 6.0 ft BOX	CHANNEL TYPE : IRREGULAR
CULVERT LENGTH = 300.0 ft	BOTTOM WIDTH = 7.0 ft
NO. OF BARRELS = 1.0	TAILWATER DEPTH = 2.8 ft
FLOW PER BARREL = 400.0 cfs	TOTAL DESIGN FLOW = 400.0 cfs
INVERT ELEVATION = 172.5 ft	BOTTOM ELEVATION = 172.5 ft
OUTLET VELOCITY = 31.1 ft/s	NORMAL VELOCITY = 17.5 ft/s
OUTLET DEPTH = 0.616 ft	

ST. ANTHONY FALLS BASIN -- FINAL DESIGN

LB = 11.9 ft   LS = 5.8 ft   LT = 7.1 ft
L = 24.8 ft   Y1 = 1.3 ft   Y2 = 8.7 ft
Z1 = 165.5 ft   Z2 = 165.4 ft   Z3 = 171.3 ft
WB = 8.2 ft   WB3 = 8.2 ft

------------------------------ CHUTE BLOCKS ------------------------------

H1 = 0.461 ft   W1 = 0.356 ft   W2 = 0.356 ft   NC = 3.000

----------------------------- BAFFLE BLOCKS ----------------------------

W3 = 1.0 ft   W4 = 1.0 ft   NB = 4
H3 = 1.3 ft   LCB = 4.0 ft

------------------------------ END SILL ----------------------------

H4 = 0.7 ft

BASIN OUTLET VELOCITY = 17.5 ft/s

Reading up to the intersection with d = 60 in, find L_a = 40 ft.

4. Apron width downstream = $d_w + 0.4\ L_a = 10 + 0.4\ (40) = 26$ ft.

5. Maximum stone diameter = $1.5\ d_{50} = 1.5\ (0.4) = 0.6$ ft.

6. Riprap depth = $1.5\ d_{max} = 1.5\ (0.6) = 0.9$ ft.

7.10 Storm Sewer Outlet End Treatment

A common failure mode of storm sewer outlets that enter perpendicularly to a main channel is erosion of the area immediately beneath the outlet of the storm sewer.

If the flow from a storm sewer outlet to a channel has velocities greater than the evasive velocity of the channel bank or bed material, some form of storm sewer outlet end treatment is required.

The energy dissipation structures described earlier in this chapter may not be applicable for dissipating energy or controlling erosion in this situation because of the main channel flows that are perpendicular to the storm sewer outlet flows.

Protection may be needed 1) below the storm sewer outlet, 2) on the channel bed, and 3) on the opposite bank. Protection of the bank below the outfall should be provided by a headwall that extends below the anticipated scour depth or by providing a riprap apron to provide protection against erosion. Protection of the channel bed can be provided by buried riprap (riprap that is flush with the channel bed). Protection of the opposite bank may be provided by riprap, vegetation or turf reinforcement.

The design of any erosion protection feature for storm sewer outlet flows must take into account the main channel flows.

Another option to dissipate energy in a storm sewer is to provide internal energy dissipation through the use of a broken back culvert. See "Hydraulic Analysis of Broken-Back Culverts" NDOR, (January 1998) for design guidance.

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